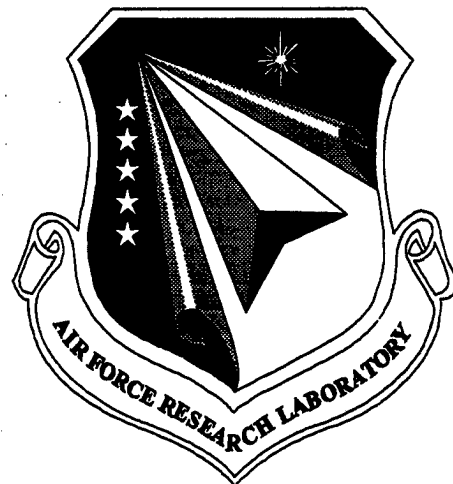


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**AFGROW USERS GUIDE AND
TECHNICAL MANUAL**

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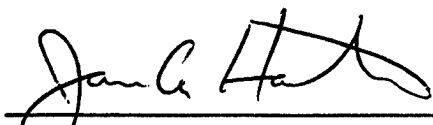
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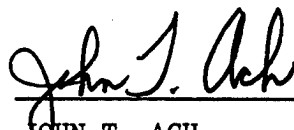
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FOREWORD

This report summarizes over 15 years of work to develop a user-friendly structural life prediction program.

The author would like to thank the U.S. Navy and Air Force for funding this effort over the last 12 years and all of the people who have provided moral support and encouragement over the years. Thanks also to Srinivas Krishnan, Alexander Litvinov, and Deviprasad Taluk for the top-notch software and finite element modeling support, which made AFGROW the best life prediction program available.

Special thanks to my wife, Cheri, for her understanding and patience during the long nights and weekends I devoted to AFGROW.

1.0 INTRODUCTION

1.1 Historical Information

AFGROW's history traces back to a crack growth life prediction program (ASDGRO), which was written in BASIC for IBM-PCs by Mr. Ed Davidson at ASD/ENSF in the early-mid 1980's. In 1985, ASDGRO was used as the basis for crack growth analysis for the Sikorsky H-53 Helicopter under contract to Warner-Robins ALC. The program was modified to utilize very large load spectra, approximate stress intensity solutions for cracks in arbitrary stress fields, and use a tabular crack growth rate relationship based on the Walker equation on a point-by-point basis (Harter T-Method). The point loaded crack solution from the Tada, Paris, and Irwin Stress Intensity Factor Handbook was originally used to determine K (for arbitrary stress fields) by integration over the crack length using the unflawed stress distribution independently for each crack dimension. After discussions with Dr. Jack Lincoln (ASD/ENSF), a new method was developed by Mr. Frank Grimsley (AFWAL/FIBEC) to determine stress intensity, which used a 2-D Gaussian integration scheme with Richardson Extrapolation which was optimized by Dr. George Sendeckyj (AFWAL/FIBEC). The resulting program was named MODGRO since it was a modified version of ASDGRO.

In 1987, James Harter came to work for the Air Force Wright Aeronautical Laboratories (AFWAL/FIBEC) and rewrote MODGRO, Version 1.X (still in BASIC for PC DOS). Over the next 2 years, a tabular crack growth rate database was added. Decreasing-increasing crack growth rate tests were performed to obtain data below $1.0\text{E-}08$ inches/cycle for 7075-T651 Aluminum and 4340 Steel. During that period, MODGRO, Version 1.X [1] included part-through flaw solutions from Newman and Raju, and standard closed-form solutions for symmetrical through-cracks (center, single edge, and double edge cracks). These solutions could also be modified for arbitrary stress fields using a Gaussian integration method with a stress distribution defined by the ratio of the unflawed stress field of interest divided by the unflawed stress field for the baseline geometry. The error in this method, of course, increases with crack length, but error in life is minor since the majority of life is consumed while the crack lengths are relatively short.

In 1989, MODGRO, Version 2.0 was rewritten in Turbo Pascal for PC-DOS as a move to a more structured computer language. At that time, Dr. George Sendeckyj provided MUCH assistance in debugging and optimizing the arithmetic operations. George was also learning the C language and was practicing by translating the BASIC code to Structured BASIC and then C at the same time I was coding it in Turbo Pascal. Runtime comparisons were made in the spirit of friendly competition. Actually, George's C version of MODGRO, Version 1.0 was faster. George was the first to have written a version of MODGRO in the C language. Additions to version 2.0 of the code included a plasticity based closure model, which was based on work by Erdogan, Irwin, Elber, M. Creager, and Sunder [2, 3, and 4]. The model is a variable amplitude closure model and more detail is contained in this report. There is also credit due to Mitch Kaplan [5] because of his good suggestion to only recalculate the beta (or alpha) values at user

defined crack growth increments. It was decided to simply use the user-input value for the Vroman integration percentage, which is normally used when analyzing blocked spectra. A real-time crack length plotting capability was also added to the program. The code was totally changed in the process, but the name MODGRO remained.

From 1990-1993 the code changed very little (still released in Turbo Pascal). Small changes/repairs were made based on errors that were discovered. The code was used to help manage the flight test program for the X-29. During high angle-of-attack maneuvers, the vertical tail experienced severe buffeting. MODGRO, Version 2.0 was used by NASA/Dryden to estimate the vertical tail life from actual flight test data collected for each flight. The use of the code allowed the Program Managers to assess the effect of various flight maneuvers on the vertical tail, and in some cases, flights were re-arranged to maximize the amount of flight data and minimize tail damage accumulation.

In 1993, the Navy was interested in using MODGRO to assist in a program to assess the effect of certain (classified) environments on the damage tolerance of aircraft. The Navy wanted to build a user-friendly code to be used in the program and initiated an agreement with WL/FIBEC to develop a state-of-the-art user interface with the added capability to perform life analysis under adverse environments. This effort required additional manpower for software development and baseline crack growth testing. On-site contract support was used to meet this requirement. Work began at that time to convert the MODGRO, Version 3.0 to the C language for UNIX to provide performance and portability to several UNIX Workstations [6]. The workstation platform was chosen to provide additional computational power for MODGRO.

In 1994, a research contract with Analytical Services and Materials was established to provide support for the Navy effort and assist in future research and development requirements of WL/FIBEC. This was when the current UNIX interface was born. In July 1994, a presentation of the results for the Navy project was given to the Navy sponsor and WL/FIBE management. After the presentation, the WL/FIBE Branch Chief (Mr. Jerome Pearson) requested that the code be renamed AFGROW, Version 3.0. Work on the Windows 95 version of AFGROW was started in October of 1996.

1.2 Current Development

Since work on the Windows95 version of AFGROW commenced in 1996, it has become the main version for new capabilities and enhancements. A composite bonded repair crack growth analysis capability was added during 1996-97. The bonded repair capability was based entirely on work by Dr. Mohan Ratwani [7]. In addition, a strain-life based crack initiation analysis capability was added. The strain-life initiation analysis capability was taken from APES, Inc. [8]. During reorganizations at Wright-Patterson AFB, it was decided that AFGROW would not receive further research and development funds. As a result, the on-site software development support provided by Analytical Services and Materials was reduced significantly. Since the Windows95 version of AFGROW had become most widely used, it was decided to discontinue the UNIX support. Recent advances in windows hardware capability has made it possible for AFGROW to equal

and even surpass the performance capabilities of many UNIX systems. The Air Force organization responsible for AFGROW development was changed from WL/FIBEC to AFRL/VASE during the most recent reorganization in 1998.

In late 1997 and early 1998, the U.S. Navy provided AFGROW funding to support a fleet tracking database development effort (FLEETLIFE) for the AV-8 Harrier. It was decided to add the Microsoft Component Object Model (COM) server technology [9] to AFGROW. This capability allows AFGROW to be used by any Windows software. Since the FLEETLIFE code was being written for the Windows platform, this provided an efficient means for the fleet tracking database to use AFGROW for structural life analyses.

The AFGROW user base continued to grow dramatically in 1998. Air Force Air Logistic Center (ALC) use and strong support for the code was greatly responsible for additional funding, provided in late 1998, for multiple crack and time dependent analysis capabilities. The Air Force Aging Aircraft Office (ASC/SMS) provided these funds. As a result of this funding and requests for UNIX support, the UNIX version of AFGROW will be upgraded to match the capabilities of the Windows version.

An experimental Power Macintosh version of AFGROW was released in late 1998 for evaluation purposes.

1.3 Future Plans

AFGROW will undergo a major overhaul in 1999 to facilitate the new multiple crack and time dependence capabilities. The multiple crack capability will allow AFGROW to analyze cases with more than one crack growing from a row of fastener holes. Stress intensity factor solutions are available for many of these cases [10, 11], but few life analysis codes have included this capability to date. The time dependent crack growth capability will provide a means of including crack growth as a function of time in addition to the standard cyclic dependence that is the default in most crack growth programs.

One of the biggest challenges to the multiple crack analysis capability is the design of the user interface. AFGROW will include a drag and drop design interface for the multiple crack capability.

As always, the developers of AFGROW will continue to listen to users comments and suggestions to improve the code.

1.4 Installing AFGROW for Windows

AFGROW, for Windows 95/98/NT4, is available for download in two forms. The first is a single self-extracting executable file that may be executed on a users PC. This file is approximately 3.5 to 4 MB in size. In case users find the single file too large to download (problem with an internet connection, etc.), AFGROW is also available in three floppy

disk images. Each file is less than 1.44MB and is “zipped” using a shareware version of the program, Winzip (available at www.winzip.com). The files should be “unzipped” to three floppy disks. The first disk contains the setup program and users will be prompted to insert disk 2 and 3 as required during the installation process.

1.4.1 The Installation Process

AFGROW uses the Install Shield© program to generate the installation program required to copy and register the required program files to an individual PC. If the single file method is used, the dialog shown in Figure 1 appears:

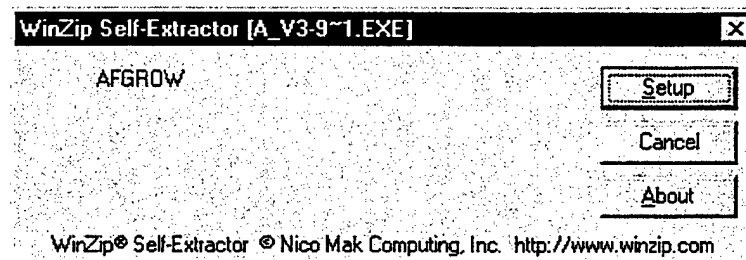


Figure 1: AFGROW Self-Extracting Setup Dialog

The installation procedure is started when the user selects the setup button in the above dialog box (Figure 1).

Once the installation has been started (using the single or multiple file methods), the following dialog (Figure 2) is displayed:

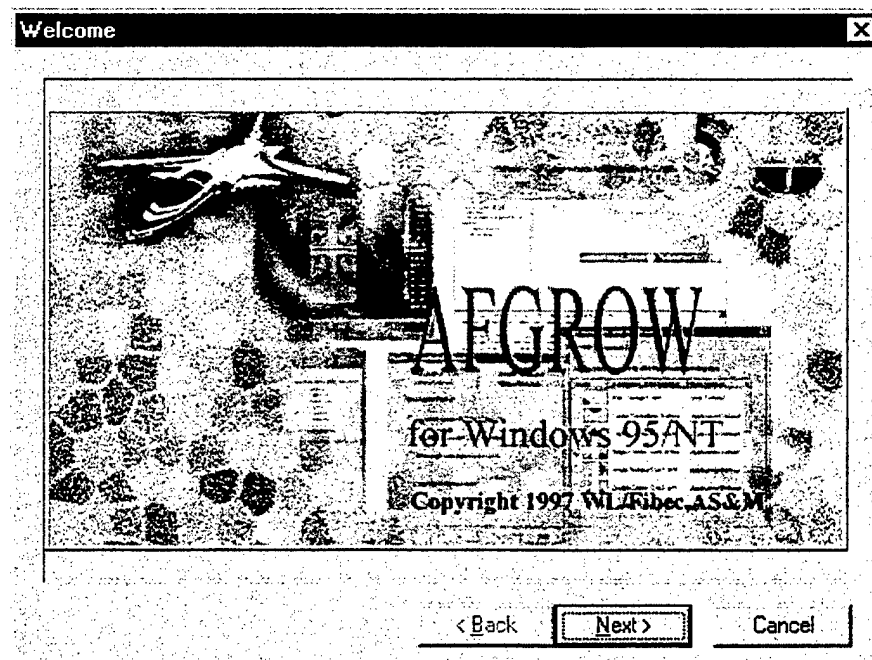


Figure 2: AFGROW Splash Screen

A blue background also appears with logos for AFRL/VASE and Analytical Services and Materials (AS&M). This splash screen is also used each time AFGROW is opened. The installation process proceeds as the user selects next (or back) on each dialog.

One of the installation dialogs (Figure 3) provides users with the option to select the directory path for the new AFGROW installation.

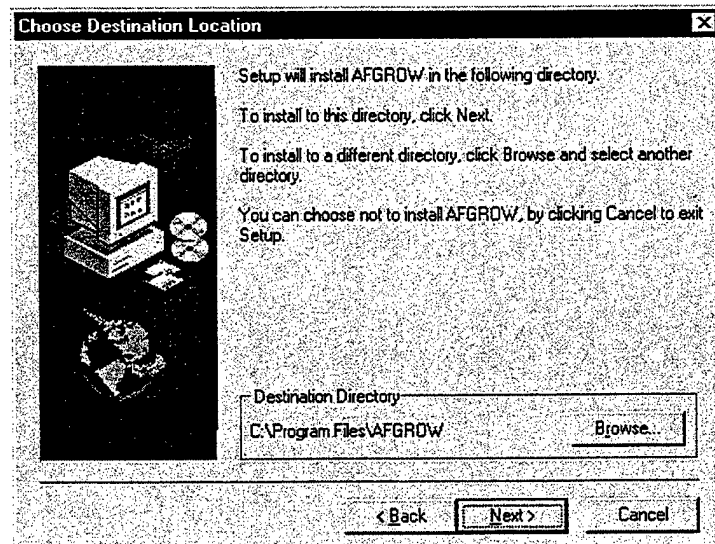


Figure 3: AFGROW Installation Directory

The default directory path is C:\Program Files\AFGROW. This is the recommended path, but may be changed as desired.

The installation will add an icon to the programs button, which is used to run AFGROW. Users are given the opportunity to change the caption for this button, in the following dialog (Figure 4):

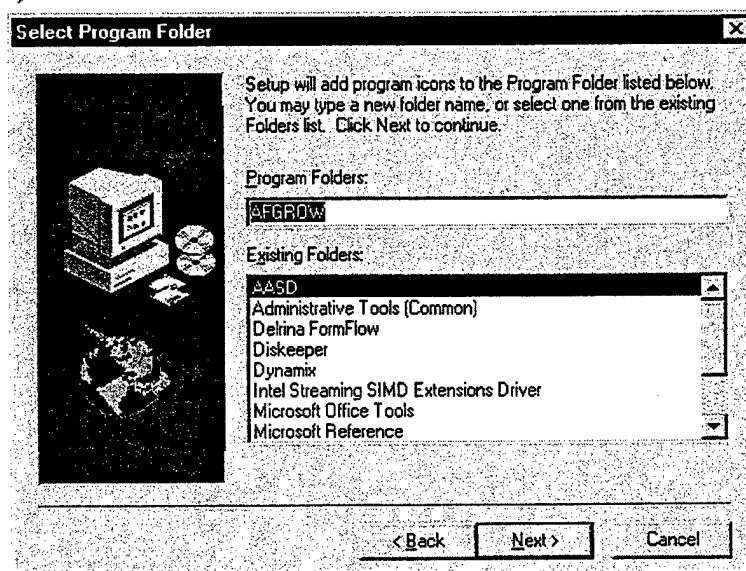


Figure 4: AFGROW Program Folder Name

It is expected that the name AFGROW will be used, but users have the option to customize the name. For example, users can include version number in the name if desired. However, do NOT attempt to install multiple versions of AFGROW since that will cause problems with the Component Object Model (COM) capabilities (see section 5.0).

The final dialog box notifies the user that the required files have been copied to the computer as shown in Figure 5.

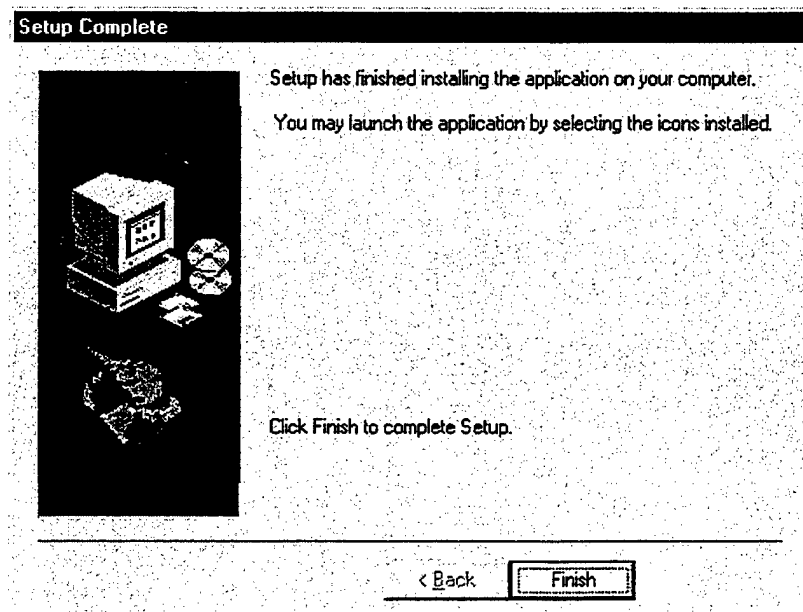


Figure 5: Final Installation Dialog

When the finish button is selected, the last thing that the installation program does is to register the required Microsoft® Active-X control(s) and provide notification of successful registration as shown below in Figure 6.

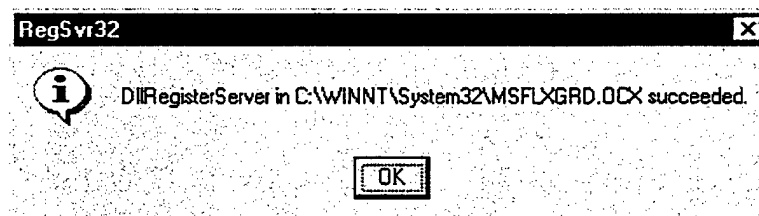


Figure 6: Notification of Successful Program Registration

AFGROW will not operate properly unless this registration is successful. This may occur if the user does not have full control of the Windows© system directories.

Users should also remember to run AFGROW as a stand-alone program to register the COM server before it can be used. If there are any problems with this process, a notification will appear the first time AFGROW is executed. If this notice appears, notify the developers of AFGROW for help in resolving the problem.

1.5 Uninstalling AFGROW for Windows

AFGROW is a fairly complex code that includes several files, libraries, and registrations that need to be properly removed before installing a new version (or simply to clear AFGROW out of a computer). The proper way to remove AFGROW is to use the Add/Remove Programs dialog in the Windows® control panel. The Add/Remove Programs dialog is shown in Figure 7.

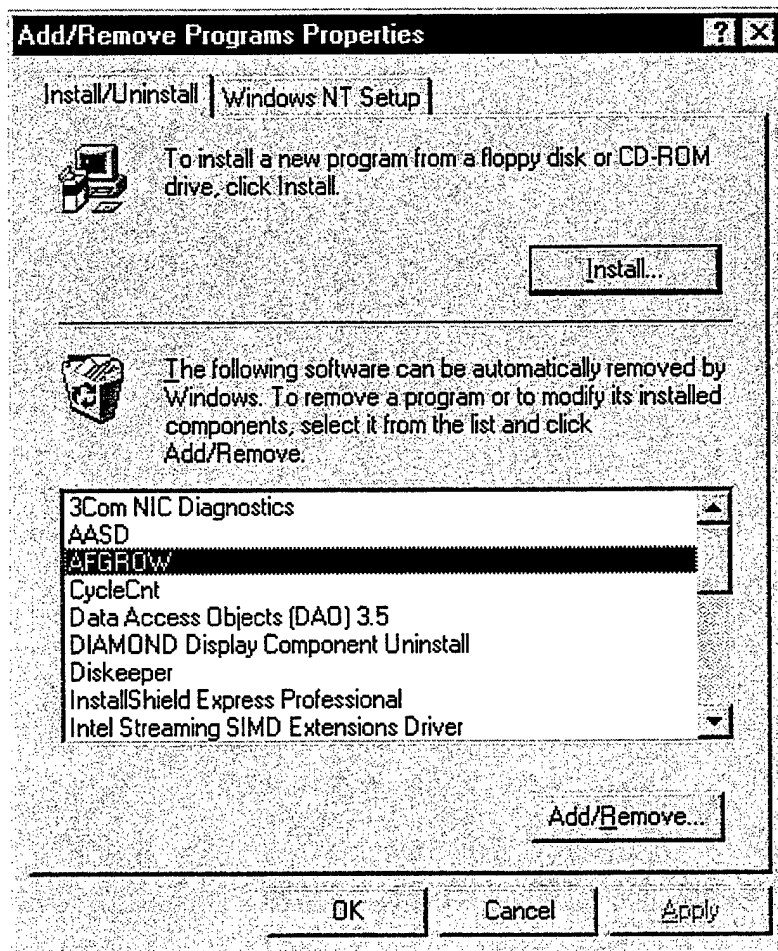


Figure 7: Add/Remove Programs Dialog

Simply select AFGROW, as shown in Figure 7, and click on the Add/Remove button and follow the subsequent instructions to complete the process.

2.0 INTERFACE FEATURES

The AGROW user interface is divided in three frames, Figure 8:

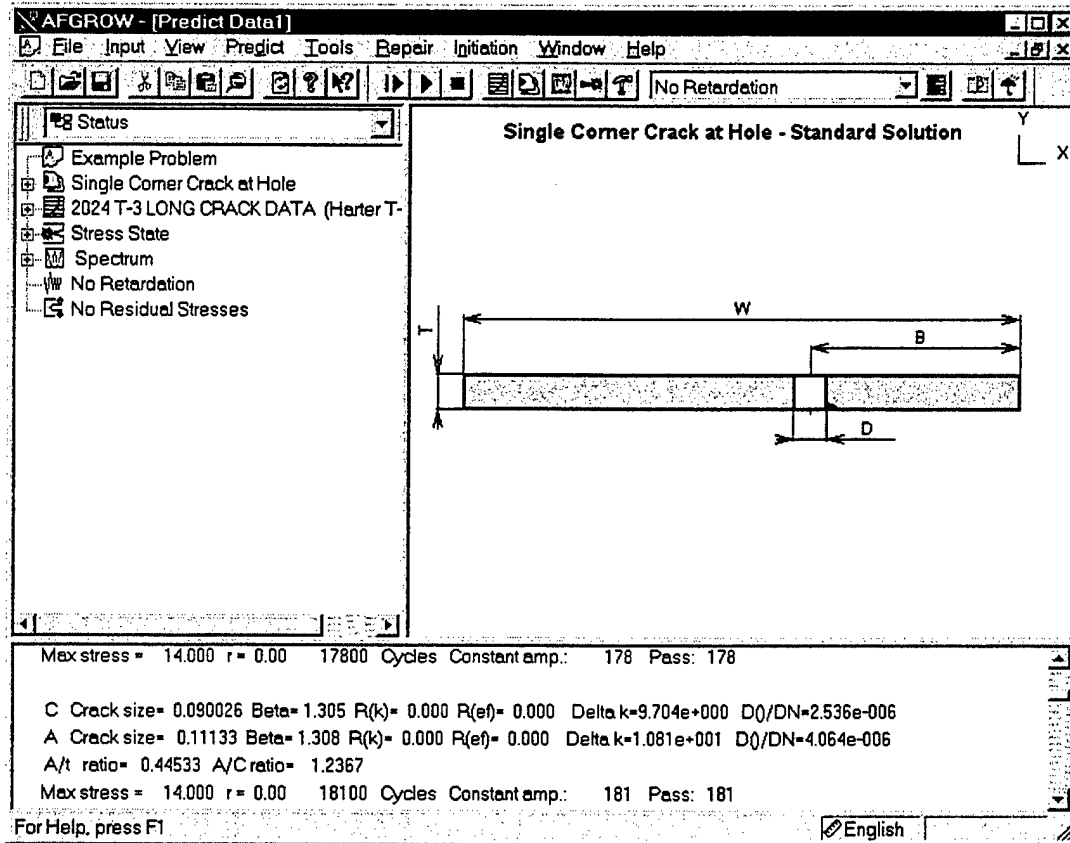


Figure 8: AFGROW Windows Graphical User Interface

Note: The frames are resized by clicking on a frame boundary and dragging it to the desired position.

2.1 Main Frame

We will refer to the upper left-hand frame as the main frame since it is used as the workhorse frame of AFGROW. The main frame has several functions, Figure 9.

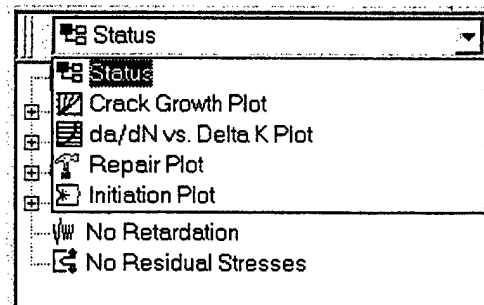


Figure 9: Mainframe Functions

The desired view may be selected using the pull-down list as shown in Figure 9 above and selecting the view of interest.

2.1.1 Status View

The status view shows the user the values of all of the input variables to be used in any life prediction, Figure 10.

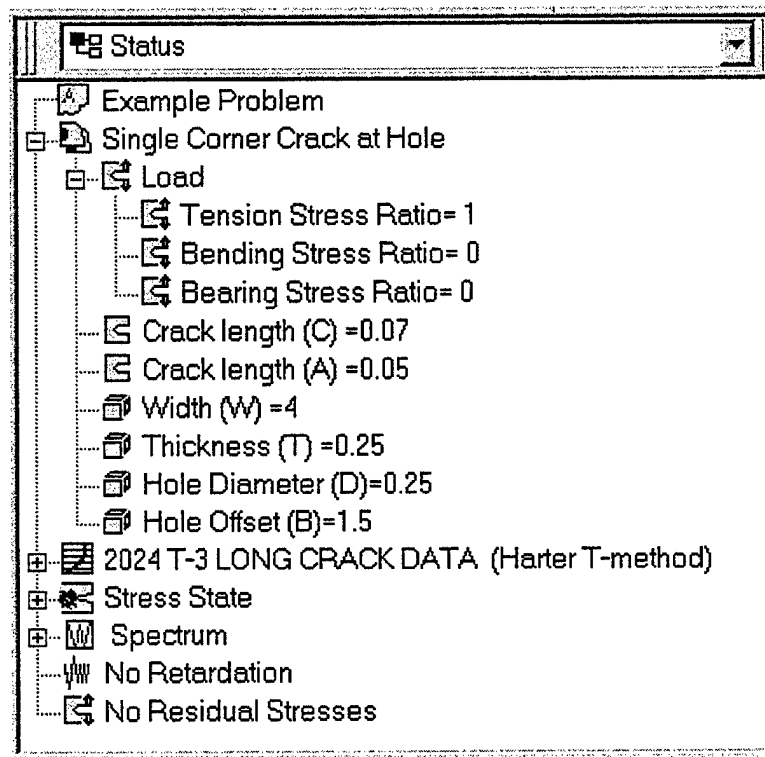


Figure 10: Status View

The view shows the major input variables with the option to expand certain variables to show more detail. A tree structure is used to expand or contract the view. Clicking on a plus (+) symbol will expand a variable list (showing more details), and clicking on a minus (-) symbol will contract the list (hiding the details).

2.1.2 Crack Growth Plot View

The crack growth plot view, Figure 11, is provided to give the user a real-time view of the crack length vs. cycles in the two possible directions of crack growth. In the case of a part through-the-thickness cracks, crack length in the thickness direction (a-direction) is displayed on the upper plot. The crack length in the width direction (c-direction) is shown in the lower plot.

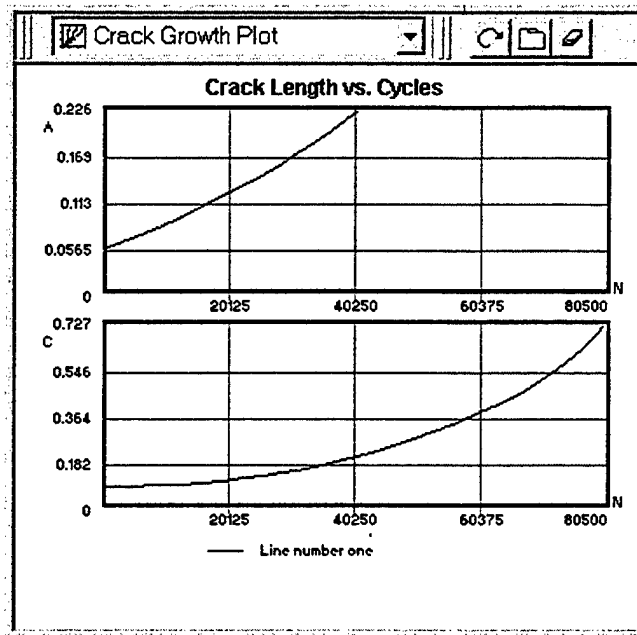


Figure 11: Crack Growth Plot View

There are several features incorporated in this view. First, we use the Microsoft rebar tool, Figure 12, to save window space and provide several useful tools.



Figure 12: Rebar Tool

The rebar tool slides to the right and left by clicking on the handle (2 vertical bars), holding the left mouse button down, and dragging the tool to the left or right.

The first tool (left most button) is the overlay tool. Clicking on this button causes the crack length plots for each prediction (up to the last eight runs) to appear on the same plot for comparison purposes.

The second tool (middle button) is the property tool. It allows the user to select various plot properties such as the plot legend, black and white plots, and reverse plotting. Reverse plotting reverses the x-axis and shows the number of cycles remaining until failure.

The third tool (right most button) is the erase tool. This tool simply erases all plots from the plot view.

2.1.3 da/dN vs. Delta K Plot View

As may be suspected, this view shows the crack growth rate versus ΔK data for the given material and crack growth rate method being used (Forman, Walker, Tabular, etc.). Data for negative R values may be handled differently for each crack growth rate model. This information is displayed at the bottom of the plot, Figure 13.

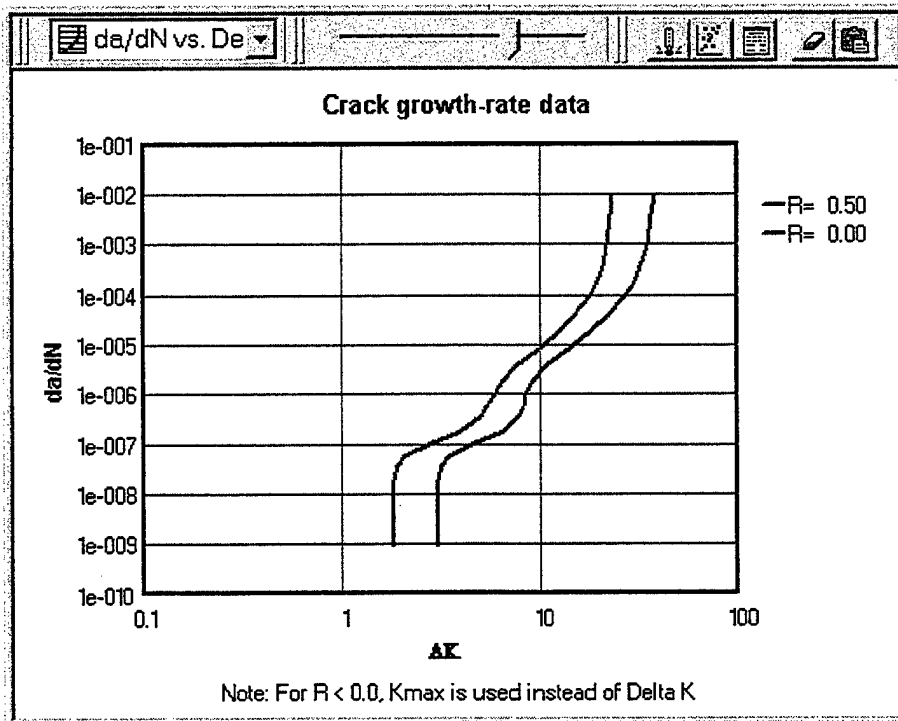


Figure 13: da/dN vs. Delta K Plot View

This view shows EXACTLY what crack growth rate data are being used for a given analysis. There are a few more tools available for this view.

First, there are two rebar tools. The first contains a slider bar that controls the stress ratio (R) for the given material. The second rebar tool contains five tools. The left most tool is a thermometer that is used to freeze a given curve so that data at several (up to 8) R values may be displayed on the same plot. The R-value for each curve is displayed on the right side of the plot. Users may double-click on the numeric value on the top element of the R legend and enter an exact value (instead of using the slider tool). The next tool (second from the left) allows tabular crack growth rate data from a text file to be overlaid on the plot for comparison. The format for this file is given in the on-line manual, or may be determined from the example file included with the AFGROW installation. The next tool allows the material data to be changed by opening the AFGROW material dialog window. The next tool (second from the right) erases any frozen curves on the plot. The last tool (right most) pastes crack growth rate data on the plot which has been copied to the Windows clipboard (from Excel, Notepad, etc.). These data merely need to exist in two columns (crack growth rate and ΔK). Prior to displaying the data, AFGROW opens a dialog box showing the minimum and maximum values of crack growth rate and ΔK and provides a means to switch the values if they are in the wrong order.

2.1.4 Repair Plot View

The repair plot view, Figure 14, shows the stress intensity correction as a function of crack length for a crack under a bonded repair.

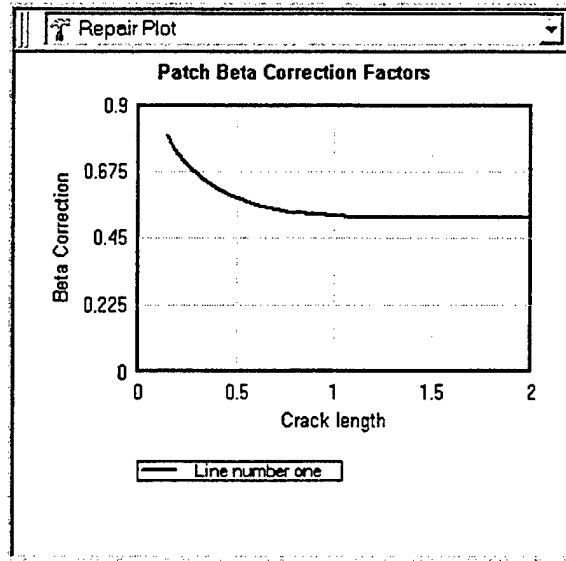


Figure 14: Repair Plot View

The correction at a given crack length (at this time, AFGROW only allows the repair option to be applied to through-the-thickness cracks) is multiplied by the applied beta factor (see section 3.2.3 on beta factors). There are no tools for this view. However, up to eight repair design curves are displayed on this plot. The user may select the curve of choice by either left clicking on the desired curve on the plot, or by right clicking on the legend for the desired curve. Three options are available: Activate, Delete, or Properties. Choosing properties will open a series of windows showing the details of the repair design for the selected curve.

2.1.5 Initiation Plot View

AFGROW uses a strain-life based crack initiation analysis method to predict crack initiation life. The initiation plot view, Figure 8, displays the cyclic stress strain or the strain-life data to be used for a given analysis.

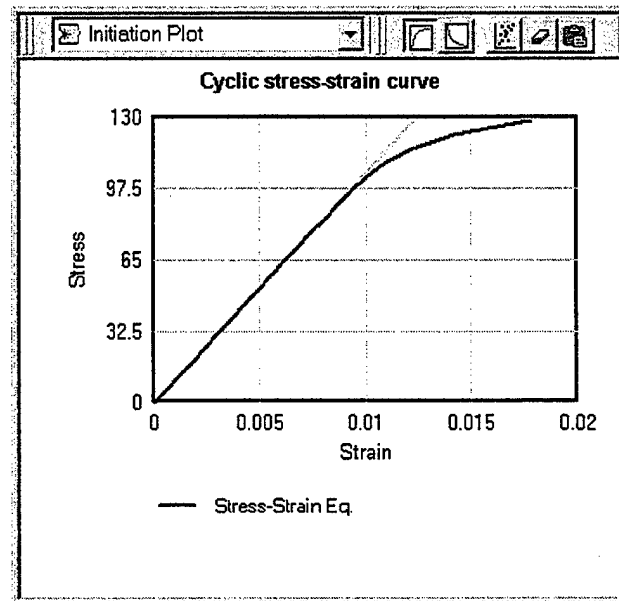


Figure 15: Initiation Plot View

The cyclic stress-strain plot includes a line representing the current Young's modulus to allow the user to verify that the appropriate modulus value is being used for the input cyclic data. If it is not correct, this must be changed in the appropriate material data dialog box.

There are five tools available for the initiation plot view. The first (left most) activates the cyclic stress-strain plot. The cyclic stress-strain curve is the locus of the endpoints of stable hysteresis loops for the given material. The next tool (second from the left) activates the strain-life plot for the given material. The strain-life data is usually obtained for small round bar specimens, but is only applicable for the given lives to a specified initial crack size. The next tool allows tabular cyclic stress-strain or strain-life data from a text file to be overlaid on the plot for comparison. The format for these files is given in the on-line manual, or may be determined from the example files included with the AFGROW installation. The next tool (second from the right) erases any overlaid data from the plot. The last tool (right most) pastes cyclic stress-strain or strain-life data on the plot, which has been copied to the Windows clipboard (from Excel, Notepad, etc.). These data merely need to exist in two columns (stress and strain or strain and life). Prior to displaying the data, AFGROW opens a dialog box showing the minimum and maximum values for each value and provides a means to switch the values if they are in the wrong order.

2.2 Animation Frame

The upper right-hand frame will be referred to as the animation frame since this frame shows a view of the crack plane (*AFGROW assumes planar crack growth*) and the crack growth is animated during the prediction process. This allows users to visualize the crack growth prediction process. The specimen view may be enlarged or diminished by simply resizing the animation frame, Figure 16.

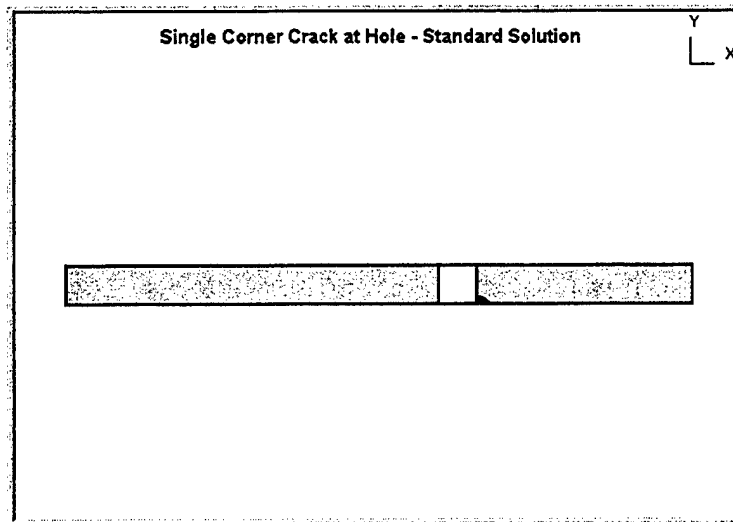


Figure 16: Animation Frame

2.2.1 Showing Specimen Dimensions

Specimen dimension definitions are displayed in the animation frame by selecting Dimensions in the View menu. The actual dimensions will not be shown since they are given in the status view, but the definitions of width (W), thickness (T), Offset (B), ... etc., will be indicated in the frame. Selecting Dimensions again in the View menu will turn off this option.

2.2.2 Refreshing the Specimen View

After an analysis, the crack will remain at the failure length in the animation frame. The specimen view may be reset to the initial crack length, by selecting Refresh in the View menu.

2.3 Output Frame

The lower frame will be referred to as the output frame, Figure 17, since it is the default location for the results of life analyses.

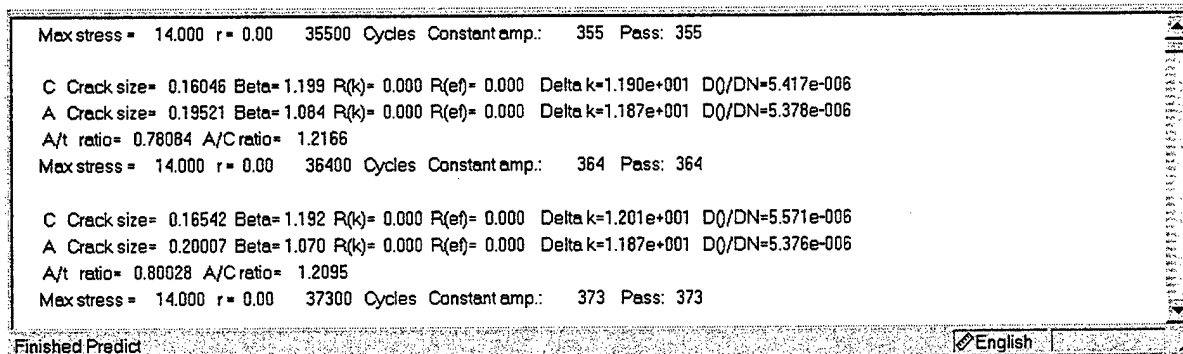


Figure 17: Output Frame

Output data consists of crack length, beta values, stress ratio, stress intensity, crack growth rate, and spectrum data.

2.4 Menu Bar

The menu bar, Figure 18, provides access to all of the features of AFGROW.



Figure 18: Menu Bar

A complete description of all of the items in the menu bar will be provided in section 3.0.

2.5 Tool Bar

The tool bar, Figure 19, is designed to provide shortcuts to many of AFGROW's most commonly used features.



Figure 19: Tool Bar

The tool bar is dockable – meaning that it can be moved and placed in other areas in the AFGROW window. To move the tool bar, click in an open area between icons and drag the tool bar to the desired location and release the mouse button.

The icons in the tool bar are designed to give a visual depiction of their purpose. In section 3, tool bar icons will be associated with the appropriate menu item.

2.6 Status Bar

The status bar, Figure 20, is located at the bottom of the AFGROW window.

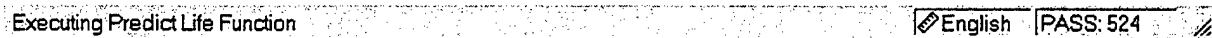


Figure 20: Status Bar

The status bar is used as the location for messages related to the status of AFGROW. A message is printed telling the user that the prediction is executing or is finished. The current system of units is displayed and may be changed by clicking (right or left) on the units icon and selecting the units of choice. Finally, the status bar prints the number or times the input spectrum has been repeated (spectrum passes) while the prediction is being executed. This may be useful for cases that require long run times since this will let users know that the code is still running.

3.0 AFGROW MENU SELECTIONS

All of the analytical features in AFGROW are accessible through the main menu (see section 2.4). The following sections will provide the details of all the available menu selections.

3.1 File Menu

The AFGROW file menu, Figure 21, contains several options as shown below.

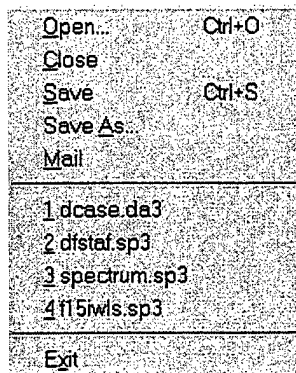


Figure 21: File Menu

As is the case with most Windows software, AFGROW stores the last few opened files that may be recalled by clicking on any one of the numbered items in the file menu. The standard selections in the file menu are described below.

3.1.1 File Open

This action allows you to choose a previously saved input file to be opened in AFGROW (see Figure 22). The following dialog will appear:

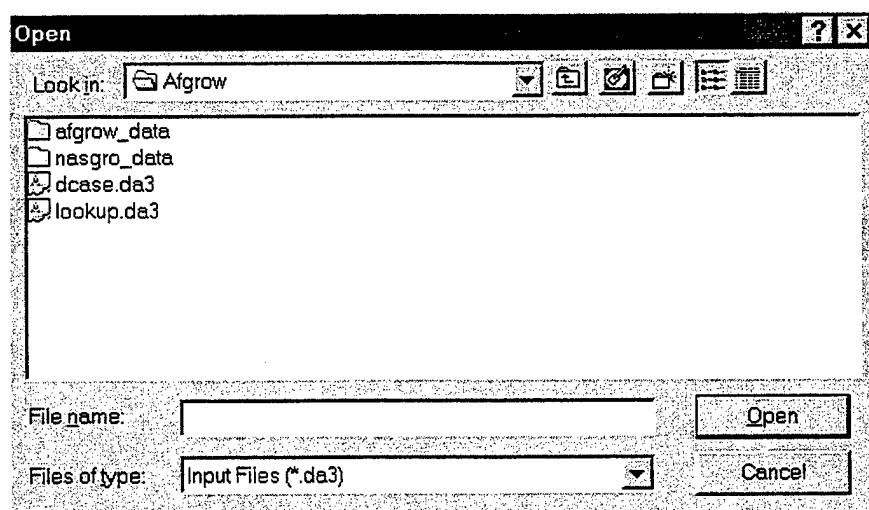


Figure 22: File Open Dialog

Simply choose the desired file, or use the dialog tools to go to another location on the computer to find the desired file. Users can double-click on the desired file, single-click on the desired file and click the Open button, or type in the file name in the File name box.

3.1.2 File Close

This action closes the active window. There are two possible windows in AFGROW. The first is the three-frame view that has been discussed in previous sections and the second is the spectrum plot view. The spectrum plot view will be discussed in a later section. If there is only one active window, closing it will leave a gray background until another file is opened or a new file is selected.

3.1.3 File Save

This action allows you to save your current input file. This option can only be used AFTER you have either opened a file or have saved the current input data with the save as option.

If the saved input data file includes a reference to a spectrum file, the spectrum file must be available in the same location to open the same spectrum file when the input file is re-opened. An error will occur if the spectrum files have been deleted or relocated since the last save.

3.1.4 File Save As

This action allows users to save their current input file as shown in Figure 23 below.

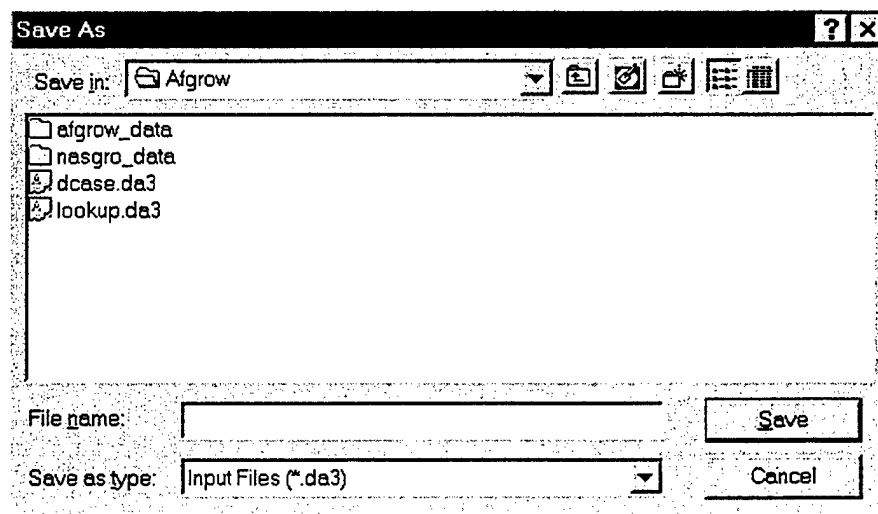


Figure 23: File Save As Dialog

Simply choose an existing file (it will be overwritten) or use the dialog tools to go to another location on your computer to save the input information. You can double-click on the desired file you want to overwrite, single-click on the desired file and click the Save button, or you can type in the file name you would like to save to in the File name box and single-click the Save button.

If the saved input data file includes a reference to a spectrum file, the spectrum file must be available in the same location to open the same spectrum file when the input file is re-opened. An error will occur if the spectrum files have been deleted or relocated since the last save.

3.1.5 File Mail

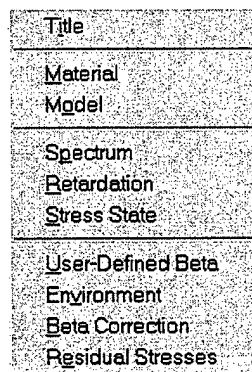
This action will activate your default e-mail client and open a new message addressed to James Harter. This is provided for your convenience for any comments or inquiries that you may have about AFGROW.

3.1.6 File Exit

This action will terminate AFGROW and completely close all open AFGROW related files.

3.2 Input Menu

The input menu, Figure 24, is the gateway for all of the information required for a standard crack growth life prediction.



Title
Material
Model
Spectrum
Retardation
Stress State
User-Defined Beta
Environment
Beta Correction
Residual Stresses

Figure 24: Input Menu

The details of the input menu are given in the following sections.

3.2.1 Input Title

The title option, Figure 25, is provided as a documentation tool. You can enter up to 80 characters in the title line to describe the problem being modeled. An additional 1000 characters may be stored in the comments area. The title dialog is shown below:

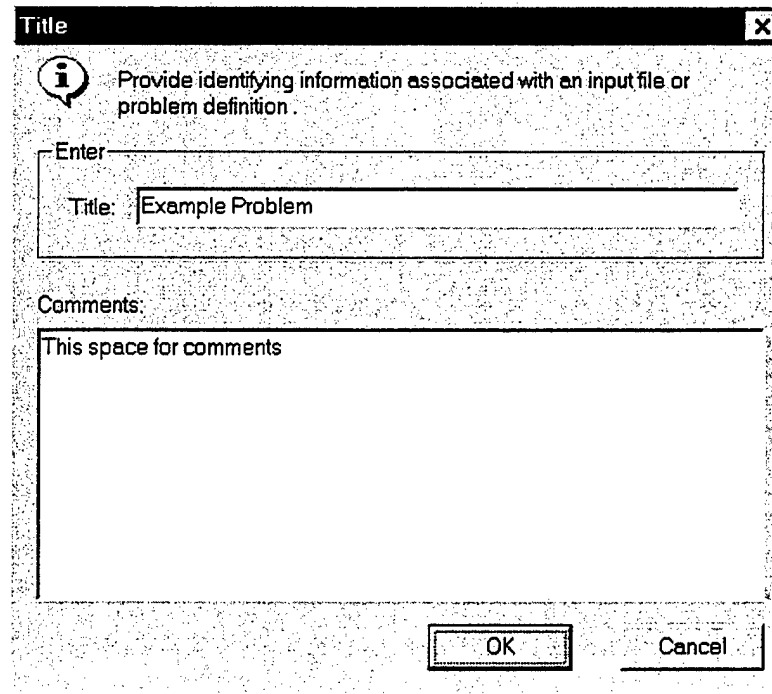


Figure 25: Input Title Dialog

3.2.2 Input Material

Toolbar Icon:



The material dialog, Figure 26, provides a means of specifying the crack growth material properties to be used by AFGROW.

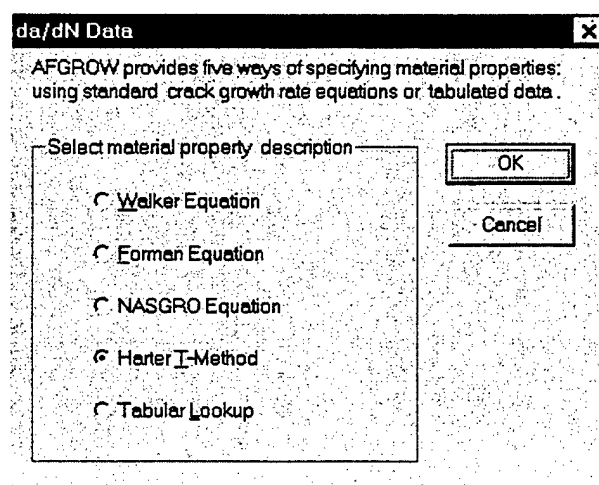


Figure 26: Input Material Dialog

The following sections contain detailed descriptions of each of the methods used to determine crack growth material properties.

3.2.2.1 Walker Equation

Walker Equation Data

The Walker equation extended the early Paris equation by allowing the shift in da/dN vs. ΔK as a function of stress ratio (R). The equation may be used in several segments to attempt to model the sigmoidal shape of the data.

Use up to 5 sets of values of 'C', 'n', and 'm'

Number of Sets:

Set	C	n	m
1	2.6e-009	3.2	0.5
2	1e-008	3	0.51
3	1e-008	3	0.5
4	1e-008	3	0.5
5	1e-008	3	0.5

Material name:

Coefficient of Thermal Expansion: Young's Modulus:

Yield Strength, YLD: Poisson's Ratio:

Plane Stress Fracture Toughness, KC:

Plane Strain Fracture Toughness, KIC: Lower limit on R shift (0..-1):

Delta K threshold value @R=0: Upper limit on R shift (<1):

Figure 27: Walker Equation Dialog

The Walker equation [12] was essentially an enhancement of the Paris Equation that included a means to account for the effect of Stress Ratio (Minimum Stress/Maximum Stress) on crack growth rate (see Figure 28).

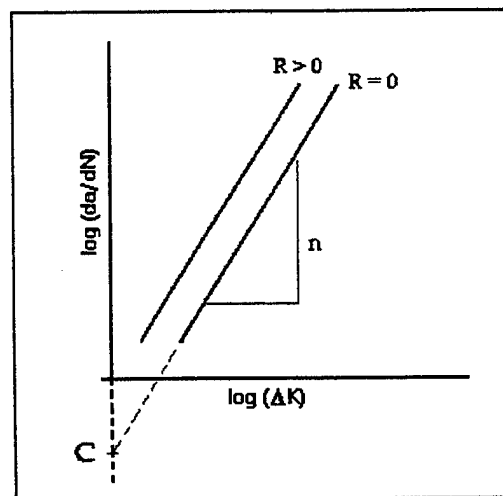


Figure 28: Walker Equation

$$\frac{da}{dN} = C[\Delta K(1 - R)^{(m-1)}]^n ; \text{ for } R \geq 0$$

$$\frac{da}{dN} = C[K_{\max}(1 - R)^{(1-m)}]^n ; \text{ for } R < 0$$

There are three reasons for using a different form of the Walker equation when R is less than 0.

First, it is more convenient to use K_{\max} in place of ΔK for negative R's. If ΔK were used for negative R values, the crack growth rate curves would continue to shift to the right as R decreases and eventually converge to a factor $(1 - R)$ of ΔK at $R=0$.

Second, the shift in crack growth rate is controlled by the term $(1 - R)^{(m-1)}$ when $R \geq 0$. In this case, $(1 - R)$ is less than 1 so that as m increases, the shift decreases. Conversely, as m decreases, the shift increases. Note: m is generally in the range [0..1). It is important that the trend in the data shifting be consistent with respect to m. Therefore, AFGROW uses the modified form of the standard Walker equation shown above for R less than 0. There seems to be a practical limit to the R shifting as R decreases below 0.0 (based on actual test data plotting da/dN vs. K_{\max}). This is why AFGROW provides the capability to set limits for R shifting (R_{lo} , R_{hi}).

Third, since AFGROW uses K_{\max} in place of ΔK for $R < 0$, the relative shifting should follow the trend that the magnitude of the shifting for a given negative R will be less than the shift for the corresponding positive R (ΔK is used for the positive R). An explanation for this may be seen in the ratio of the crack opening stress to maximum stress ratio (C_f) as a function of R (stress ratio). The change in the opening stress ratio, Figure 29, tends to decrease as R decreases causing the change in effective stress intensity (and growth rate) to decrease. This trend forces the shifting of growth rate to be less for negative R values than for the corresponding positive values. The use of the exponent $(1-m)$ applied to $(1-R)$ ensures that the appropriate trend in rate shifting will be maintained.

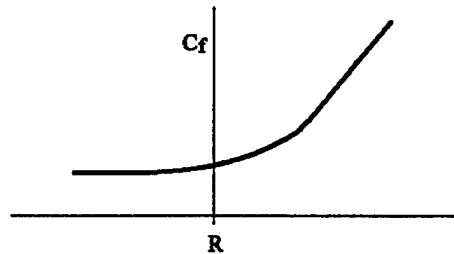


Figure 29: Closure Factor vs. Stress Ratio

AFGROW allows up to 5 Walker line segments to provide the best possible fit to actual crack growth rate data. The current implementation of the Walker equation allows users to assign different m -values for each segment. (see Figure 30).

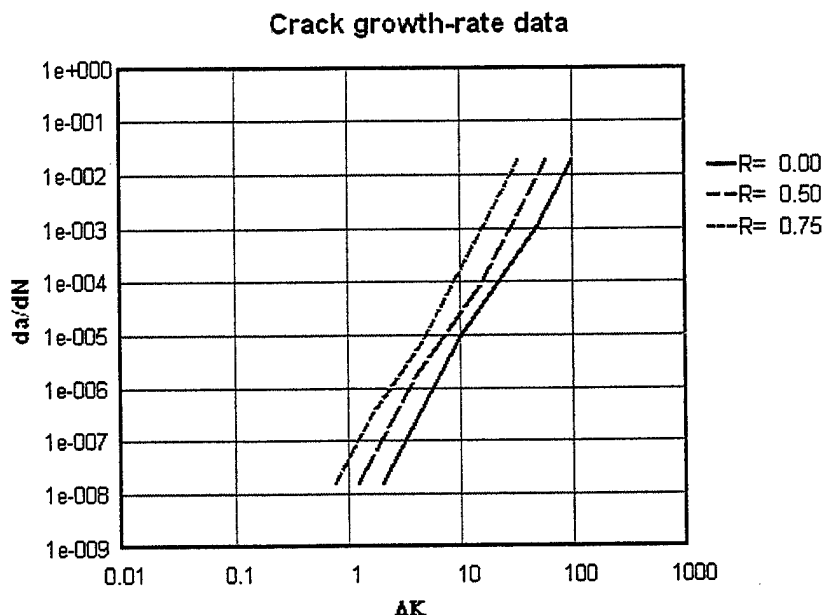


Figure 30: Using the Walker Equation with Multiple Segments

AFGROW automatically calculates the intersection points for each segment at any R value. Users are responsible for the integrity of the input data, but AFGROW will check to ensure that the following conditions are true:

- Intersection Points (for $R = 0$) are Monotonically Increasing (in terms of da/dN and ΔK)
- Segment Slopes are Always Positive
- Adjacent Slope Values (n) Must NOT Match
- Adjacent Intercept Values (C) Must NOT Match
- Threshold ΔK Values Must be Less Than ΔK_c for all R Values

The use of unequal m values may result in discontinuous crack growth rate curves. Although AFGROW checks to be sure that the intersection points for the Walker segments are monotonically increasing for $R=0$, it is possible that the intersection points will NOT be increasing in terms of da/dN and ΔK for other R values. This is an important issue since it has a large impact on the crack growth rates that will result in these cases. AFGROW will NOT allow any crack growth rate curve to result in multiple crack growth rates for a given ΔK . If AFGROW detects this condition for any R value, users will have the option to limit the range of possible R values or allow portions of the curve that fall below the ΔK value for the intersection of previous line segment to be ignored (as shown in Figure 31). The crack growth rate will jump to the value for the appropriate line

segment that corresponds to the ΔK value for the intersection point prior to the error condition. If the rate jump exceeds the maximum rate allowed for a given analysis, AFGROW will only plot (and use) the data to the last intersection and assign the maximum rate to any ΔK values that exceed the value at the last intersection.

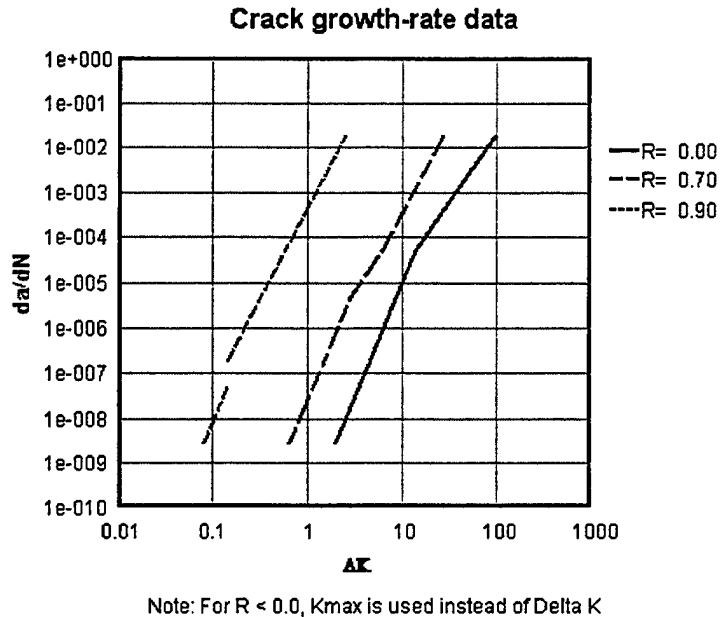


Figure 31: Discontinuous Crack Growth Rate Curves

Remember that the range of possible crack growth rate values is controlled by ΔK threshold and the plane stress fracture toughness (K_{Ic}) – both at $R=0$. AFGROW calculates ΔK threshold and ΔK_{Ic} for each R value using the crack growth rate for each term at $R = 0$. These crack growth rates determine the lower and upper bounds on crack growth rate values. Points below the lower limit ($< \Delta K$ threshold) will be assumed to result in no crack growth rate, and those above the upper limit will be assigned a crack growth rate value equal to the upper limit. Regardless of the number of segments used, **only data in the current range of possible crack growth rates will be used or shown in the crack growth rate plots.**

The following is a description of the terms used in the Walker dialog box.

The following parameters are ONLY used in the analysis of bonded composite repairs:

Coefficient of Thermal Expansion: (Temperature)⁻¹ Used in the calculation of the thermal effect of patch cure temperature on the stress intensity factor of the patched metal.

Young's Modulus: (Stress) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch (*also used in the initiation module*).

Poisson's Ratio: (Non-Dimensional) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch.

The following parameters are used in the standard crack growth analysis:

C: (Stress⁽⁻ⁿ⁾, Length^(1-n/2)) Value of da/dN when R=0 and Delta K=1 (da/dN intercept).

n: (Non-Dimensional) Paris Exponent (da/dN slope).

Walker Exponent, m: (Non-Dimensional) Normal Range (0-1) Controls shift in crack growth rate data, curve shift decreases as m increases.

Plane Stress Fracture Toughness (KC): (Stress, Length^{0.5}) Value of Fracture Toughness to be used under pure plane stress conditions.

Plane Strain Fracture Toughness (KIC): (Stress, Length^{0.5}) Value of Fracture Toughness to be used under pure plane strain conditions.

Delta K Threshold Value @ R=0, THOLD: (Stress, Length^{0.5}) Threshold stress intensity value at R=0 - no crack growth will be calculated when Delta K is below threshold for a given R value.

Yield Strength, YLD: (Stress) Yield stress (0.2% strain) for the metal being analyzed.

Lower limit on R shift, Rlo: (Non-Dimensional) R value below which no further R shifting is calculated.

Upper limit on R shift, Rhi: (Non-Dimensional) R value above which no further R shifting is calculated.

Buttons:

APPLY: Apply the current parameters.

READ: Read a file containing Walker parameters.

SAVE: Save the current parameters to a file.

CANCEL: Cancel the dialog box.

OK: Accept the current parameters and close the dialog box.

3.2.2.2 Forman Equation

Material- Forman Equation

Material Properties Forman Constants

Enter

Delta K threshold value @R=0, THOLD: 2

Upper limit on R shift, RHl (Max 1.0): 0.75

Lower limit on R shift, RLO (0...-4.0): -1

☒ Do not Use RCUT

RCUT: 0

Select

☐ Map R ☐ if ☐ <= R <= ☐ R = ☐

Forman Curve for RLO <= R <= RCUT

Number of Sets: 1

Set	C	n	K cut
1	2.6e-009	3.2	=KC
2	1	1	1
3	1	1	1

Forman Curve for RCUT < R <= RHl

Number of Sets: 0

Set	C	n	K cut
1	1	1	=KC
2	1	1	1
3	1	1	1

OK Cancel Apply Save Read

Figure 32: Forman Equation Dialog

The Forman equation [13], named for Dr Royce Forman, was an improvement of the Walker equation that included a means to account for the upper portion of the da/dN vs. Delta K curve where the data become asymptotic to the value of Delta K at fracture (see Figure 33).

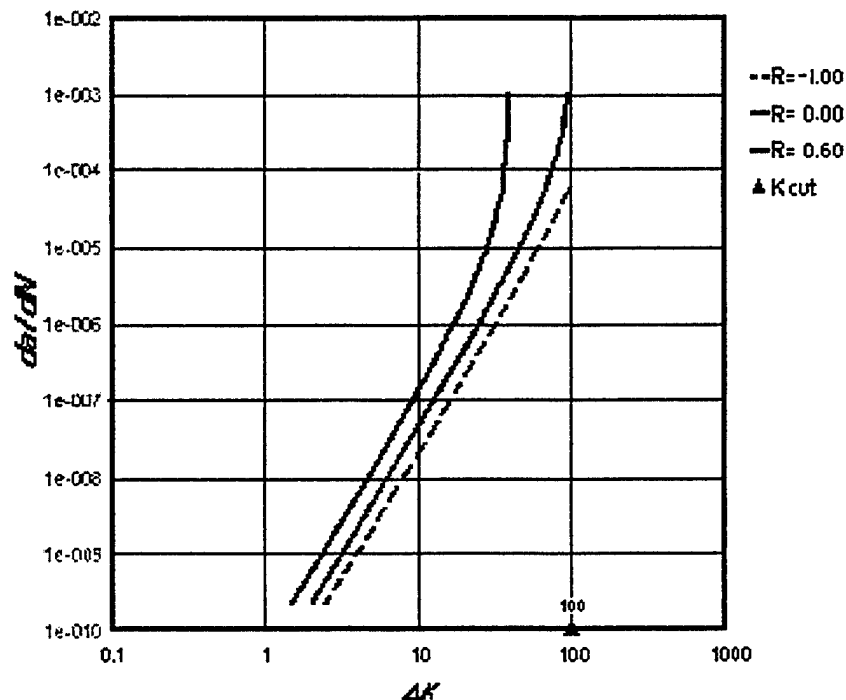


Figure 33: Forman Equation

The form of the Forman equation used in AFGROW is shown here.

$$\frac{da}{dN} = \frac{C \Delta K^n}{((1-R)K_c - \Delta K)}$$

A weakness of the Forman equation lies in a lack of flexibility in modeling data shifting as a function of stress ratio (R). There is no parameter to adjust the R shift directly. The amount of shifting is controlled by the plane stress fracture toughness of a given material.

The material properties, used with the Forman equation, are accessible in a separate tab of the Forman dialog box as shown in Figure 34 (simply click on the material properties tab):

Material-Forman Equation

Material Properties | **Forman Constants**

The Forman equation has been used by several investigators to characterize da/dN vs. Delta K behavior. The equation results in linear behavior in log-log space in the low and mid-range, and allows the upper end of the data to curve upward, modeling the near-failure behavior of metals.

Enter

Material Name: User defined data

Coefficient of Thermal Expansion: 1.25e-005

Young's Modulus: 10500

Poisson's Ratio: 0.33

Yield Strength, YLD: 56

Plane Strain Fracture Toughness, KIC: 35

Plane Stress Fracture Toughness, KC: 100

OK Cancel Apply Save Read

Figure 34: Forman Equation Material Property Dialog

AFGROW allows up to 3 Forman segments (or sets – see Figure 32) to provide the best possible fit to actual crack growth rate data. Users are permitted to define up to 2 fits (3 segments each) as a function of stress ratio (R). If a second fit is desired for R greater than a given value (Rcut), simply uncheck the [Do not Use RCUT] box and enter the desired Rcut value in the appropriate field. AFGROW also allows users to map the Forman fit for a given R to a range of R-values. This option may be useful if users would like to limit the R shift to a certain value. It should be noted that although the Forman equation uses the Paris equation in its numerator, it IS NOT equivalent to the Paris equation because of the terms in the denominator. It is important to note here that when using the Forman equation, AFGROW allows the use of Delta K to include negative K when R < 0.0. **This is the ONLY exception to the normal standard in AFGROW.** This exception results in a shift in crack growth rate data to the right of the R= 0.0 data when R < 0.0.

The current Forman dialog provides a GREAT deal of flexibility in handling crack growth rate data with a closed-form equation.

The following parameters are **ONLY** used in the analysis of bonded composite repairs:

Coefficient of Thermal Expansion: (Temperature)-1 Used in the calculation of the thermal effect of patch cure temperature on the stress intensity factor of the patched metal.

Young's Modulus: (Stress) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch (*also used in the initiation module*).

Poisson's Ratio: (Non-Dimensional) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch.

The following parameters are used in the standard crack growth analysis:

C: ($\text{Stress}^{(1-n)}$, $\text{Length}^{((3-n)/2)}$) Value of $da/dN * (Kc-1)$ when $R=0$ and $\Delta K=1$.

n: (Non-Dimensional) Paris Exponent (in this case, limit in da/dN slope as ΔK approaches 0.0).

Kcut: (Non-Dimensional) Value of Stress Ratio (R) defining the highest R allowed for the first Forman curve fit (leftmost curve fit in Forman Constants dialog box).

Kcut: (Stress , $\text{Length}^{0.5}$) Value of ΔK (at $R=0$) defining the highest ΔK allowed for the given segment (upper segment boundary) - Note, the Kcut for the last defined segment is assumed to be equal to the plane stress fracture toughness of the metal being analyzed.

Plane Strain Fracture Toughness (KIC): (Stress , $\text{Length}^{0.5}$) Value of Fracture Toughness to be used under pure plane strain conditions.

Plane Stress Fracture Toughness (KC): (Stress , $\text{Length}^{0.5}$) Value of Fracture Toughness to be used under pure plane stress conditions.

Yield Strength, YLD: (Stress) Yield stress (0.2% strain) for the metal being analyzed.

The following parameters may be used in the retardation models in AFGROW:

Delta K Threshold Value @ R=0, THOLD: (Stress , $\text{Length}^{0.5}$) Threshold stress intensity value at $R=0$ - this parameter is required by the Willenborg retardation model. It is NOT currently used in crack growth rate calculations. At this time, there is no lower bound on da/dN in the Forman equation in AFGROW. The only limit occurs when the

total crack growth after one spectrum pass is $< 1.0E-13$ (in whatever length units are being used).

Lower limit on R shift, Rlo: (Non-Dimensional) R value below which no further R shifting is calculated.

Upper limit on R shift, Rhi: (Non-Dimensional) R-value above which no further R shifting is calculated.

Buttons:

OK: Accept the current parameters and close the dialog box.

CANCEL: Cancel the dialog box.

APPLY: Apply the current parameters.

SAVE: Save the current parameters to a file.

READ: Read a file containing Forman parameters.

3.2.2.3 NASGRO Equation

The NASGRO equation [14], used in NASA's crack growth life prediction program, NASGRO, Version 3.0 is now available in AFGROW. Those who are familiar with the NASGRO equation may notice a few additional parameters in the NASGRO equation dialog (see Figure 35). The additional values are required by AFGROW (explained later in this section).

Material- NASGRO Equation

Material Properties | **NASGRO Equation Constants**

i The NASGRO equation was developed by Forman and Newman at NASA, de Koning at NLR and Henriksen at ESA. It is an attempt to use a closed-form equation to model the da/dN vs. Stress Intensity behavior of engineering materials.

Enter

Material name: User defined data

Coefficient of Thermal Expansion: 1.25e-005

Young's Modulus: 10500

Poisson's Ratio: 0.33

Yield Strength, YLD: 40

Plane Strain Fracture Toughness, KIC: 25

Plane Stress Fracture Toughness, KIC: 60

Effective Fracture Toughness for part-through-the-thickness cracks, KIE: 50

Fit parameter in KC versus Thickness Equation, Ak: 1

Fit parameter in KC versus Thickness Equation, Bk: 0.5

OK Cancel Apply Save Read...

Figure 35: NASGRO Equation Dialog

Forman and Newman at NASA, De Koning at NLR, and Henriksen at ESA developed the elements of the NASGRO (Version 3.0) crack growth rate equation. It has been implemented in AFGROW as follows:

$$\frac{da}{dN} = C \left[\left(\frac{1-f}{1-R} \right) \Delta K \right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K} \right)^p}{\left(1 - \frac{K_{max}}{K_{crit}} \right)^q}$$

Where C, n, p, and q are empirically derived, and

$$f = \frac{K_{op}}{K_{max}} = \begin{cases} \max(R, A_0 + A_1 R + A_2 R^2 + A_3 R^3) & R \geq 0 \\ A_0 + A_1 R & -2 \leq R < 0 \\ A_0 - 2A_1 & R < -2 \end{cases}$$

The coefficients are:

$$A_0 = (0.825 - 0.34\alpha + 0.05\alpha^2) \left[\cos\left(\frac{\pi}{2} S_{\max} / \sigma_0\right) \right]^{\frac{1}{\alpha}}$$

$$A_1 = (0.415 - 0.071\alpha) S_{\max} / \sigma_0$$

$$A_2 = 1 - A_0 - A_1 - A_3$$

$$A_3 = 2A_0 + A_1 - 1$$

Here, α is the plane stress/strain constraint factor, and S_{\max}/σ_0 is the ratio of the maximum applied stress to the flow stress. These values are provided by the NASGRO material database for each material.

$$\Delta K_{th} = \Delta K_0 \left(\frac{a}{a + a_0} \right)^{\frac{1}{2}} / \left(\frac{1 - f}{(1 - A_0)(1 - R)} \right)^{(1 + C_{th}R)}$$

Where:

- ΔK_0 - threshold stress intensity range at $R = 0$
- a - crack length (a or c in AFGROW)
- a_0 - intrinsic crack length (0.0015 inches or 0.0000381 meters)
- C_{th} - threshold coefficient

The values for ΔK_0 and C_{th} are provided by the NASGRO material database for each material.

The NASGRO equation accounts for thickness effects by the use of the critical stress intensity factor, K_{crit} .

$$\frac{K_{crit}}{K_{Ic}} = 1 + B_k e^{-\left(A_k \frac{t}{t_0}\right)^2}$$

Where:

- K_{Ic} - plane strain fracture toughness (Mode I)
- A_k - Fit Parameter
- B_k - Fit Parameter
- t - thickness
- t_0 - reference thickness (plane strain condition)

The plane strain condition is:

$$t_0 = 2.5(K_{Ic} / \sigma_{ys})^2$$

The values for K_{Ic} , A_k , and B_k are provided by the NASGRO material database for each material.

For part-through cracks, the NASGRO equation uses a variable, K_{Ie} (in the database), in place of K_{crit} . The value, K_{Ie} , is a material constant since the developers of the NASGRO equation felt that the K_{crit} value of a part-through crack is not highly dependent on thickness. The value, K_{crit} , is calculated internally and is ONLY used by AFGROW to determine da/dN . It is NOT used as a failure criterion. The variable, K_c , printed in the dialog box is NOT the K_{crit} shown above (see note¹ below).

The NASGRO equation constants are accessible in the equation constant tab, Figure 36, of the dialog box.

Material- NASGRO Equation

Material Properties NASGRO Equation Constants

The parameters required for the NASGRO equation are given below. AFGROW requires additional parameters (Rhi and Rlo) to provide limits for the curve shifting. It has been demonstrated that these limits may be necessary for the NASGRO equation.

Enter

Paris crack growth rate constant, C:	1.32e-009
Paris exponent in NASGRO Equation, n:	2.95
Exponent in NASGRO Equation, p:	0.5
Exponent in NASGRO Equation, q:	0.5
Threshold stress intensity factor range at R = 0, DK0:	7
Threshold coefficient, Cth:	1.506
Plane stress/strain constraint factor, Alpha:	2.5
Ratio of the maximum applied stress to the flow stress, Smax/S0:	0.3
Upper limit on R shift, RHI (Max 1.0):	0.7
Lower limit on R shift, RLO (0... -2.0):	-0.3

OK Cancel Apply Save Read...

Figure 36: NASGRO Equation Constants

These values are set when a material is selected from the NASGRO material database. AFGROW requires a few parameters that are not directly required for the NASGRO

¹ Please note that AFGROW uses the plane strain (K_{Ic}) and plane stress (K_c) fracture toughness values to interpolate a value for the critical stress intensity factor failure criterion. There is a difference between NASGRO and AFGROW in this regard. Therefore, the value (K_c) shown in the NASGRO dialog is really the value of K_{crit} determined by setting $t=0$ in the above equation for K_{crit} / K_{Ic} . This is done to provide a means of estimating the plane stress fracture toughness for a given material for use by AFGROW.

equation. AFGROW uses the variables R_{lo} and R_{hi} to set stress ratio limits. It was discovered that the parameters for many of the materials in the NASGRO database would cause the crack growth rate curves to behave erratically above or below certain stress ratios. The crack growth rate curves can become vertical ($K_{th} = K_{crit}$). To avoid this, AFGROW will check for this problem and automatically set R_{hi} and R_{lo} when a material is selected. If parameters are edited manually, care should be taken to verify that this problem will not occur (use the da/dN vs. Delta K plot view in the main frame – see section 2.1.3).

The material database for the NASGRO equation is extensive (361 Materials). Selecting the READ button, Figure 37, at the bottom of the main dialog allows access the database:

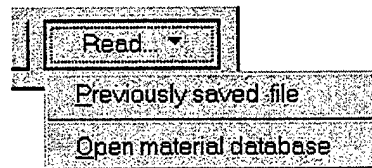


Figure 37: Opening the NASGRO Material Database

AFGROW allows you to open a previously saved file for a material which may not be available in the database (if a user has their own data or has modified data in the NASGRO database), or to open a special browser, Figure 38, to navigate through the large database.

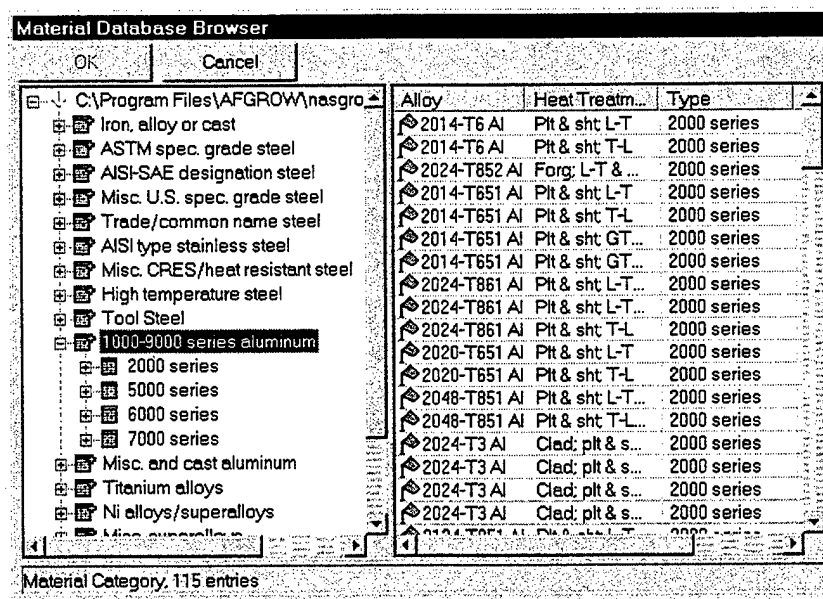


Figure 38: Material Database Browser

The browser was designed using a tree structure to aid in locating a desired material. First, select the material by category (or alloy type) by double clicking on the name or clicking on the plus sign to expand the list of materials for the given category, sub-

category, heat treatment and material form. Once a material has been selected, the parameters are displayed as shown in Figure 39:

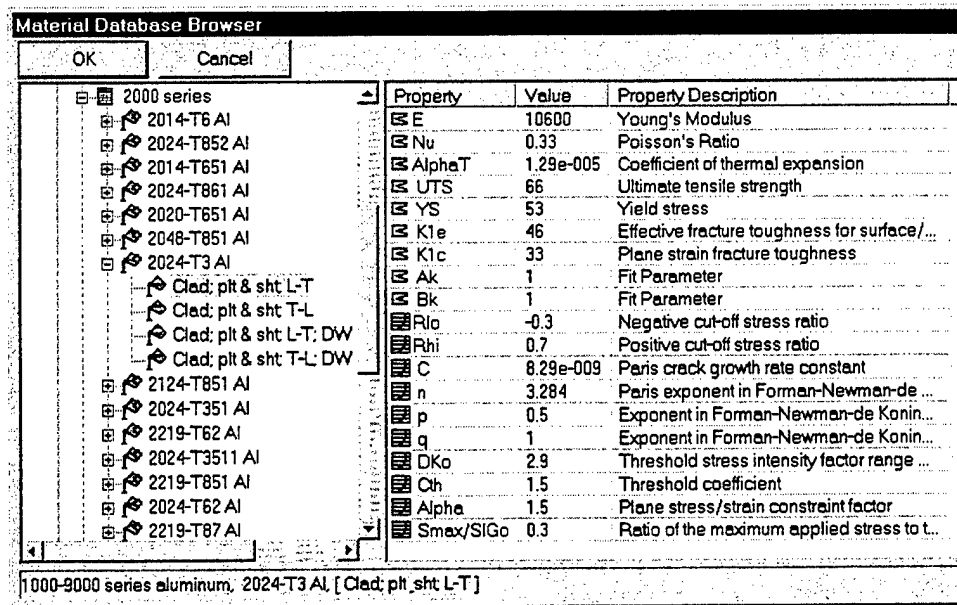


Figure 39: Database Material Selection

At this point, pressing the OK button will complete the material selection process. It should be noted that this window may be inside the previous (parent) window and the OK button for the parent window could be visible. Remember that the OK button for the material database browser is at the upper left-hand corner of its window.

The following parameters are **ONLY** used in the analysis of bonded composite repairs:

Coefficient of Thermal Expansion: (Temperature)-1 Used in the calculation of the thermal effect of patch cure temperature on the stress intensity factor of the patched metal.

Young's Modulus: (Stress) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch (*also used in the initiation module*).

Poisson's Ratio: (Non-Dimensional) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch.

The following parameters are used in the standard crack growth analysis:

C: (Stress⁽⁻ⁿ⁾, Length^(1-n/2)) Paris Coefficient.

n: (Non-Dimensional) Paris Exponent.

p: (Non-Dimensional) NASGRO Equation Exponent.

q: (Non-Dimensional) NASGRO Equation Exponent.

C_{th}: (Non-Dimensional) Threshold Coefficient.

Alpha: (Non-Dimensional) Plane stress/strain constraint factor.

S_{max}/σ₀: (Non-Dimensional) Maximum applied stress to flow stress ratio.

Yield Strength, YLD: (Stress) Yield stress (0.2% strain) for the metal being analyzed.

Plane Strain Fracture Toughness (K_{IC}): (Stress, Length^{0.5}) Value of Fracture Toughness to be used under pure plane strain conditions.

Plane Stress Fracture Toughness (K_C): (Stress, Length^{0.5}) Value of Fracture Toughness to be used under pure plane stress conditions.

K_{Ic}: (Stress, Length^{0.5}) Effective fracture toughness for part through-the-thickness cracks - ONLY used in place of K_{crit} in the NASGRO equation for crack growth rate calculations for part through-the-thickness cracks (not a failure criterion).

A_k: (Non-Dimensional) Fit parameter in K_{crit}/K_{Ic} vs. thickness equation.

B_k: (Non-Dimensional) Fit parameter in K_{crit}/K_{Ic} vs. thickness equation.

The following parameters may be used in the retardation models in AFGROW:

ΔK₀: (Stress, Length^{0.5}) Threshold stress intensity factor range at R=0.

R_{lo}: (Non-Dimensional) Lower limit on R shift.

R_{hi}: (Non-Dimensional) Upper limit on R shift.

Buttons:

OK: Accept the current parameters and close the dialog box.

CANCEL: Cancel the dialog box.

APPLY: Apply the current parameters.

SAVE: Save the current parameters to a file.

READ: Read the NASGRO material database OR a file containing NASGRO equation parameters.

3.2.2.4 Harter T-Method

Dr. Joseph Gallagher (University of Dayton Research Institute) first coined the name (Harter T-Method [15]) in 1994 and it has since replaced the original name – “Point-by-Point Walker Shift Method.” In 1983, James A. Harter first developed the method as a means to interpolate and/or extrapolate crack growth rate data using a limited amount of tabular crack growth rate test data. The Harter T-Method dialog is shown in Figure 40.

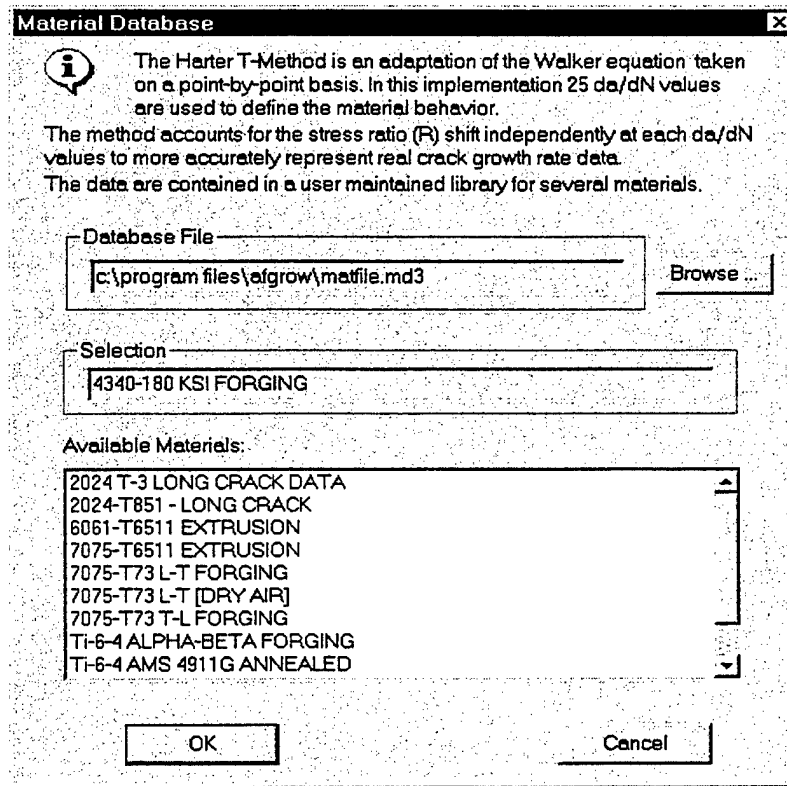


Figure 40: Harter T-Method Dialog

Tabular crack growth rate data are provided in a database file (of sorts). The tabular data are provided as an option to users and users are encouraged to create their own file or files using data of your own choice. AFGROW provides the ability to browse your system to look for tabular material data files. The file extension (.md3) is used since the file has a set format and is the tabular material data format used by AFGROW, Version 3.X. The tabular data utilizes the Walker equation on a point-by-point basis (Harter T-Method) to extrapolate/interpolate data for any R value.

AFGROW uses the Walker equation on a point-by-point basis (Harter T-Method) to determine crack growth rate shifting as a function of stress ratio. Using standard AFGROW practices, K_{max} is used in place of ΔK when $R < 0$. The data shifting is handled as follows:

$$\frac{da}{dN} = C[\Delta K(1 - R)^{(m-1)}]^n ; \text{ Walker Equation}$$

At a given da/dN , the relationship reduces to:

$$\Delta K = \Delta K_{R=0} (1 - R)^{(1-m)} ; \text{ for } R \geq 0.0$$

$$K_{\max} = \Delta K_{R=0} (1 - R)^{(m-1)} ; \text{ for } R < 0.0$$

Note that K_{\max} is used in place of ΔK when $R < 0$. Although not algebraically correct, it is important that the proper trend in R shift be maintained. This trend is that as m increases, the R shift decreases. This method is simply a way to interpolate/extrapolate data in log-log scale by using the exponential form. This method has given very good results over the years.

It is usually very difficult to obtain crack growth rate data over a sufficient range of crack growth rate and R values to allow the use of simple interpolation methods to accurately model material behavior. A matrix large enough to allow that would consist of actual test data for at least 7 decades of crack growth rate, several R values (positive and negative), and cover the entire range of rate and R values required for the spectrum being analyzed. The Harter T-Method, Figure 41, allows the use of as much data as is available (of course, more data is better) and experience is very useful when data are limited.

Here's how it works:

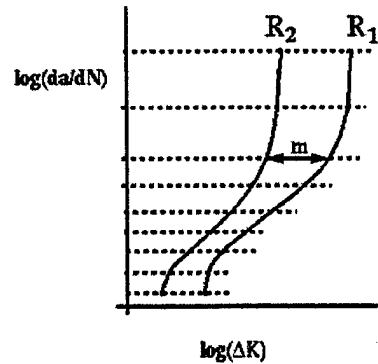


Figure 41: Harter T-Method Crack Growth Rate Shifting as a Function of R

Using the Walker equation (see above) at a single crack growth rate for two positive R values, the following relationship is seen:

$$\Delta K_1 (1 - R_1)^{(m-1)} = \Delta K_2 (1 - R_2)^{(m-1)}$$

Solving for m yields:

$$m = 1 + \left[\log_{10} \left(\frac{\Delta K_1}{\Delta K_2} \right) / \log_{10} \left(\frac{(1 - R_2)}{(1 - R_1)} \right) \right] ; \text{ for } R_1 \text{ and } R_2 \geq 0$$

For the reasons stated above, the method to handle negative stress ratios simply involves using K_{\max} in place of ΔK and switching the exponent for the negative R as follows:

$$K_{\max 1} (1 - R_1)^{(1-m)} = \Delta K_2 (1 - R_2)^{(m-1)}$$

Solving for m yields:

$$m = 1 + \left[\log_{10} \left(\frac{K_{\max 1}}{\Delta K_2} \right) / \log_{10} ((1 - R_1)(1 - R_2)) \right] ; \text{ Where } R_1 < 0.0 \text{ and } R_2 \geq 0.0$$

For two negative R values, the relationship becomes:

$$K_{\max 1} (1 - R_1)^{(1-m)} = K_{\max 2} (1 - R_2)^{(1-m)}$$

Solving for m yields:

$$m = 1 - \left[\log_{10} \left(\frac{K_{\max 1}}{K_{\max 2}} \right) / \log_{10} \left(\frac{(1 - R_2)}{(1 - R_1)} \right) \right] ; \text{ Where } R_1 < 0.0 \text{ and } R_2 < 0.0$$

It is important to know the significance of the value of m. The value, m, is non-dimensional and has no real physical significance. The value of m is merely a mathematical means of controlling the shift of the crack growth rate data as a function of stress ratio (R).

The n (slope) value in the Walker Equation gets cancelled when the equations for 2 R values are set equal at a given da/dN. All m does is provide a means of determining the R shift on a point by point basis. All that is required is to take ΔK (or K_{\max} if $R < 0$) for two R values at the same crack growth rate, apply the appropriate equation, and an appropriate m may be calculated for the given crack growth rate. This method may be repeated at several rate values to describe the tabular data for any R value. AFGROW uses da/dN and Delta K (for $R=0$) and m at 25 crack growth rate values (da/dN) to recreate the da/dN, Delta K (or K_{\max}) curve for any R desired using the method described above. However, the recreated data are determined for the same rate values in the input table. AFGROW calculates the curve (really just the ΔK s or K_{\max}) for each rate until the K value exceeds the current K value of interest. Then it just does a logarithmic interpolation between the last two points in the curve (points on each side of the current stress intensity) to give the current rate. This can save a great deal of CPU time.

There are a few RULES that should be adhered to:

- K_{\max} is used in place of Delta K when $R < 0.0$ - All curves shift left of $R=0.0$
- Normally, the R shift for negative R values will stop for $R < [-0.2 \text{ to } -0.5]$ (Rlo)

- It is NOT advisable to use data for $R < R_{lo}$ to determine m values
- Normal range for m is [0-1]
- R_{lo} may be determined using m values determined for R values > -0.2 by finding which negative R returns the curve for $R \leq -0.5$
- Shift for positive R is $>$ negative R values for the same absolute R value
- For adjacent points, m should not change abruptly

The format that is required for the material data file [filename.md3] is as follows (space delimited):

[Title] (up to 35 characters - should include units being used)

[da/dN] [Delta K @ $R=0.0$] [m] (25 lines of these data – EXACTLY 25 lines)

[R_{lo}] [R_{hi}] [KIC] [Yield]

[Modulus] [Poisson's ratio] [Coefficient of Thermal Expansion]

The above is repeated for each material in the file. The LAST line requires the word, *END* to denote the end of material data. See additional notes² on the use of this method in AFGROW

The following parameters are ONLY used in the analysis of bonded composite repairs:

Coefficient of Thermal Expansion: (Temperature)-1 Used in the calculation of the thermal effect of patch cure temperature on the stress intensity factor of the patched metal.

Young's Modulus: (Stress) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch (*also used in the initiation module*).

Poisson's Ratio: (Non-Dimensional) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch.

² When using the Harter T-Method in AFGROW, the threshold value of Delta K is taken to be the Delta K value (for $R=0$) corresponding to the lowest rate value of the table. AFGROW handles the shifting for the current R value internally. The maximum Delta K value for $R=0.0$ in the tabular data is assumed to be the plane stress fracture toughness (K_c) which is used to determine fracture under pure Plane Stress conditions. AFGROW expects 25 values of crack growth rate, Delta K (at $R=0.0$), and m . Please be sure to use 25 points, no more or less! For now, the units for this method **MUST** be English (Ksi, inches, degrees F). The conversion to metric units will be done by AFGROW internally if required.

The following parameters are used in the standard crack growth analysis:

Walker Exponent, m: (Non-Dimensional) Normal Range (0-1) Controls shift in crack growth rate data - curve shift decreases as m increases.

Plane Strain Fracture Toughness (KIC): (Stress, Length^{0.5}) Value of Fracture Toughness to be used under pure plane strain conditions.

Delta K Threshold Value @ R=0, THOLD: (Stress, Length^{0.5}) Threshold stress intensity value at R=0 - no crack growth will be calculated when Delta K is below threshold for a given R value.

Yield Strength, YLD: (Stress) Yield stress (0.2% strain) for the metal being analyzed.

Rlo: (Non-Dimensional) R value below which no further R shifting is calculated.

Rhi: (Non-Dimensional) R value above which no further R shifting is calculated.

Buttons:

BROWSE: Browse system to find *.md3 files.

CANCEL: Cancel the dialog box.

OK: Except the current choice and close the dialog box.

.

3.2.2.5 Tabular Look-Up

Tabular LOOKUP Data

Input values of Delta_K for up to 30 da/dN values and up to 10 different R(stress ratio) values.
 Matrix must have at least two R values and two da/dN values.
 Input Delta_K for R >= 0; input Kmax for R < 0.0

Number of da/dN Sets: Number of R Sets:

		R[1]	R[2]
		0.1	0.6
da/dN[1]	1.000e-009	2.606	1.38
da/dN[2]	3.000e-009	2.636	1.409
da/dN[3]	1.000e-008	2.673	1.503
da/dN[4]	2.000e-008	2.685	1.66
da/dN[5]	4.000e-008	2.729	1.897

Material name:

Young's Modulus:
 Poisson's Ratio:

Coefficient of Thermal Expansion:
 Upper limit on da/dN, DADNHI:
 Lower limit on da/dN, DADNLO:

Plane Stress Fracture Toughness, KIC:
 Yield Strength, YLD:

Plane Strain Fracture Toughness, KIC:
 Lower limit on R shift (Max 0):

Delta K threshold value @R=0:
 Upper limit on R shift (0, 1):

OK Cancel Save Read Apply

Figure 42: Tabular Look-Up Dialog

A tabular look-up crack growth rate capability is provided in AFGROW to allow users to input their own crack growth rate curves. The tabular data utilizes the Walker equation on a point-by-point basis (Harter T-Method) to extrapolate/interpolate data for any R value (see section 3.2.2.4). The difference in the tabular lookup method is that the user doesn't have to calculate all of the m values (AFGROW does it internally between each possible pair of input R curves).

It is usually very difficult to obtain crack growth rate data over sufficient crack growth rate range and R values to use simple interpolation methods to accurately model material behavior. However, the tabular look-up option provided in AFGROW allows a user to enter crack growth rate vs. stress intensity data for as few as two R values. The Harter T-Method allows you to use as much data as you have (of course, more data is best) and you can use the method to interpolate and extrapolate data within user specified limits.

Here's how it works:

First, obtain da/dN vs. stress intensity data for at least 2 R-values, which provides a satisfactory fit to test data. It is necessary to input stress intensity data at each R at equal crack growth rate values. It is simply too difficult to allow users to input independent da/dN vs. stress intensity curves for each R. Using the same rate values for all R ensures that the data covers the same range of crack growth rate. It would be very difficult to develop a program to interpolate or extrapolate the data otherwise.

Set the values for the number of da/dN sets and R sets at the top of the dialog (see Figure 42) and enter the crack growth rate data in the matrix.

Enter the appropriate material property data for all fields in the lower half of the dialog box. AFGROW provides optional default material property values if the user wishes help with these parameters. The default values are merely typical properties for the materials listed. There is also a choice to add zeros to all of these data fields. This help is available by clicking on the default icon as shown in Figure 43 below:

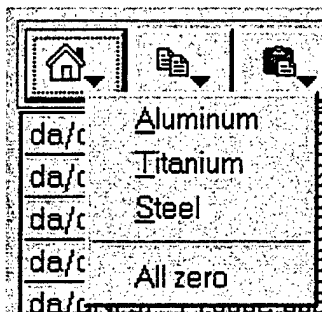


Figure 43: Tabular Look-Up Default Material Data

AFGROW includes the option to copy the crack growth data to the Windows clipboard to allow it to be pasted into another Windows application (i.e., Excel 7 or Excel 8). The entire table (excluding the parameters below the table), a single column, or a single row may be copied (see Figure 44). When copying a column or row, you must first click on the row or column to be copied.

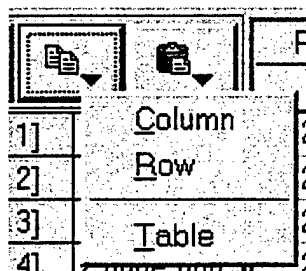


Figure 44: Tabular Look-Up Copy Choices

Data that have been placed in the Windows clipboard from another Windows application (i.e. Excel 7 or Excel 8) may be pasted into AFGROW (see Figure 45). If the application is not in Excel format, be sure that the data are tab delimited in each row. When pasting a column or row, you must first click on the row or column where the data is to be pasted.

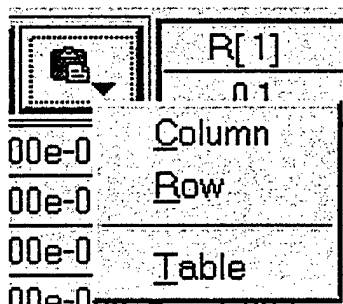


Figure 45: Tabular Look-Up Paste Choices

If Excel is used to create the crack growth rate data table, the required format is shown in Figure 46:

dadN/R	0.1	0.6
1.00E-09	2.606	1.38
3.00E-09	2.636	1.409
1.00E-08	2.673	1.503
2.00E-08	2.685	1.66
4.00E-08	2.729	1.897
6.00E-08	2.792	2.089
1.00E-07	2.954	2.355

Figure 46: Excel Spreadsheet Example for Crack Growth Rate Data

Error and Warning Checking:

Use the APPLY button to perform required error and warning checks on the data. Some tips are available for help dealing with the error messages.

When errors are detected in the user-input data, AFGROW will usually tell the user where the error is. If the error is in the crack growth rate data matrix, the coordinates of the location of the error are given.

Errors that are found for extrapolated data may be difficult to debug. The easiest way to find the problem in these cases is to reduce the limits on R or crack growth rate (see Figure 42) to make them closer to the limits of the entered data until the error message(s) stop. The next step is to use the crack growth rate plotting capability in AFGROW to examine the data. It may be obvious where the error is after viewing the plots and scrolling between the upper and lower limits on R (Rlo and Rhi).

The following error checks are performed:

- Positive R curves may NOT cross each other in the domain of the crack growth rate and R limits input by the user
- Negative R curves may NOT cross each other in the domain of the rate and R limits input by the user
- ΔK (or K_{max}) values for a given R MUST increase with increasing rate
- ΔK values for increasing positive R must decrease for increasing R
- K_{max} values for decreasing negative R must decrease for decreasing R
- K_{max} values for negative R values must be less than ΔK for $R = 0.0$
- Threshold ΔK value at $R=0$ must be in the range of ΔK for $R=0$ within the crack growth rate limits input by the user
- K_{IC} must be less than K_C
- RLO must be less than or equal to 0.0
- RHI must be greater than 0.0 AND less than 1.0

The following warning checks are performed:

- Data for negative R (K_{max}) should be greater than the data (ΔK) at the same positive R
- K_{max} values for negative R should be greater than data at $R=0$ when converted to ΔK ($\Delta K = K_{max}*(1-R)$ - AFGROW will do this conversion internally)

Once the tabular data have been entered and applied (error checked), it may be saved in a file by clicking on the save button in the tabular look-up dialog. The format that is required for the tabular lookup data file [filename.lkp] is as follows (space delimited):

[No. of da/dN values] (2 min., 30 max.) [No. of R values] (2 min., 10 max.)

[R_1] [R_2] [R_{max}]

[da/dN_1] [$DK @ R_1$] [$DK @ R_2$] ... [$DK @ R_{max}$]

[da/dN_2] [$DK @ R_1$] [$DK @ R_2$] ... [$DK @ R_{max}$]

.....

[da/dN_{max}] [$DK @ R_1$] [$DK @ R_2$] ... [$DK @ R_{max}$]

[R_{lo}] [K_{IC}] [$DADNLO$] [$Yield$]

[R_{hi}] [K_C] [$DADNHI$] [$THOLD$]

[$Poisson's\ ratio$] [$Coefficient\ of\ Thermal\ Expansion$] [$Modulus$]

Remember that K_{max} is required in place of ΔK for $R < 0.0$.

The following parameters are ONLY used in the analysis of bonded composite repairs:

Coefficient of Thermal Expansion: (Temperature)-1 Used in the calculation of the thermal effect of patch cure temperature on the stress intensity factor of the patched metal.

Young's Modulus: (Stress) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch (*also used in the initiation module*).

Poisson's Ratio: (Non-Dimensional) Used in the calculation of the stress intensity factor correction due to the presence of the bonded patch.

The following parameters are used in the standard crack growth analysis:

DADNLO: (Length) Lower limit for da/dN extrapolation (uses log-log linear extrapolation based on the first two user input points for the appropriate R).

DADNHI: (Length) Upper limit for da/dN extrapolation (uses log-log linear extrapolation based on the last two user input points for the appropriate R).

Plane Stress Fracture Toughness (KC): (Stress, Length^{0.5}) Value of Fracture Toughness to be used under pure plane stress conditions.

Plane Strain Fracture Toughness (KIC): (Stress, Length^{0.5}) Value of Fracture Toughness to be used under pure plane strain conditions.

Delta K Threshold Value @ R=0: (Stress, Length^{0.5}) Threshold stress intensity value at R=0 - no crack growth will be calculated when Delta K is below threshold for a given R value.

Yield Strength, (YLD): (Stress) Yield stress (0.2% strain) for the metal being analyzed.

Lower Limit on R Shift: (Non-Dimensional) R value below which no further R shifting is calculated.

Upper Limit on R Shift: (Non-Dimensional) R value above which no further R shifting is calculated.

Buttons:

OK: Accept the current (first does the error checking) choice and close the dialog box.


CANCEL: Cancel the dialog box.

SAVE: Save the current data to a user specified file.

READ: Read a previously saved file (*.lkp default extension).

APPLY: Apply the current input values to check for any errors.

3.2.3 Input Model

Toolbar Icon: 

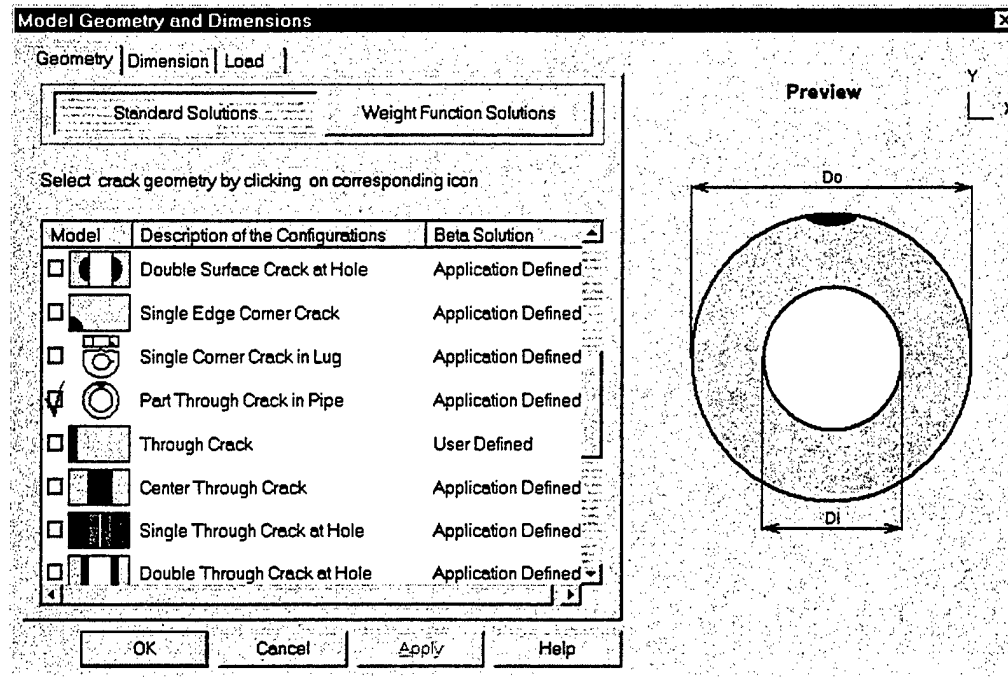


Figure 47: Input Model Dialog

There are two types of stress intensity factor solutions available in AFGROW:

- Standard Stress Intensity Solutions
- Weight Function Stress Intensity Solutions

In addition to these solutions, users can input their own solutions through the user input beta option. However, to use this option, the user must first select either the 1-D or 2-D user defined geometry from the Standard Solutions dialog. The user can also choose to use one of the Standard Solutions and apply a beta correction based on the ratio of the actual stress distribution to the standard stress distribution.

3.2.3.1 Standard Stress Intensity Solutions

The standard crack geometries in AFGROW consist of several models for which closed form or tabular stress intensity factor solutions are available. Solutions for several geometries are built into the code and are referred to as application defined solutions. AFGROW also allows user defined stress intensity solutions to be input in the form of beta factors at various crack lengths. Beta factors are defined as follows:

$$\beta = \frac{K}{\sigma \sqrt{\pi x}} ; \text{ Where } x \text{ is the appropriate crack length}$$

The crack length dimension in the thickness direction is the a-dimension and the crack length in the width direction is the c-dimension. Many of the standard stress intensity solutions in AFGROW use the popular Newman and Raju curve fit solutions to finite element results [16]. An angle, ϕ , is used in these equations to determine the stress intensity value for the crack growth dimensions (a, and c). This angle is defined as shown in Figure 48:

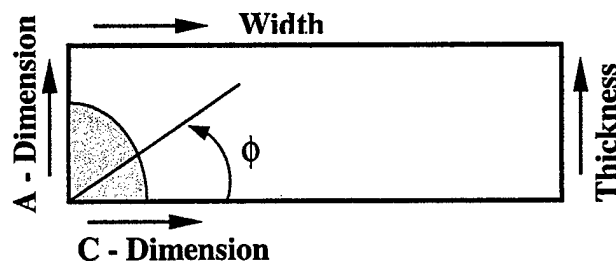


Figure 48: Angle Used in Newman and Raju Solutions

The angle is measured from a line in the c-direction beginning at the crack origin. The closed-form Newman and Raju solutions do not necessarily match the finite element results at the free edges. Care was taken in AFGROW to use the angle for each crack dimension that tends to match the published finite element results near the free edges. The angles used in the Newman and Raju solutions for each crack dimension are documented in the following sections for models that use these solutions.

Application and user defined solutions are identified under the beta solution column in the geometry tab of the model dialog (see Figure 47). There are only two user-defined models among the standard solutions since AFGROW currently models only 1-D or 2-D cracks. The currently available standard solutions are described in the following sections.

3.2.3.1.1 Part Through-the-Thickness Crack (User Defined)




This model is used when a user has an existing stress intensity factor solution (in the form of a beta table) for any 2-D crack, which may be described with two length dimensions (2-D) to input in AFGROW.

The geometric beta values are NOT calculated by AFGROW, but are merely interpolated from a two-dimensional user-defined table of beta values. Users must supply beta values at various crack lengths so that the appropriate value at a given crack length may be interpolated. This model is shown as a corner cracked plate in the animation frame. The representation of the model is merely meant to indicate the two dimensional nature of the crack. It was not possible to create representations of all possible geometries that may be modeled using user defined beta factors

For the [a] crack length dimension: $K = \sigma \sqrt{\pi a} \beta(a)$

For the [c] crack length dimension: $K = \sigma \sqrt{\pi c} \beta(c)$

Once this model is selected, AFGROW will add a user input beta icon, , in the AFGROW toolbar (if active). A blinking indication will also be activated in the status view of the main frame window indicating that user-defined beta information is required. Users may choose any external source to calculate stress intensity factors and convert them to beta values. The details of the 2-D user-defined beta option are given in section 3.2.7.2.

Once the 2-D beta information has been entered, the user will be prompted to enter beta values for the 1-D case (see section 3.2.7.1). The 1-D user-defined beta table is used after the 2-D crack transitions to become a 1-D (through-the-thickness) crack.

3.2.3.1.2 Center Semi-elliptic Surface Crack (Application Defined)



Tension Loading:

Reference [16]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 90°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Bending Loading:

Reference [16]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 90°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

3.2.3.1.3 Center Semi-elliptic Edge Surface Crack (Application Defined)



Tension Loading:

Reference [16]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 90°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

3.2.3.1.4 Center Full-elliptic Embedded Crack (Application Defined)



Tension Loading:

Reference [16]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 90°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

3.2.3.1.5 Single Corner Crack at Hole (Application Defined)



Tension Loading:

Reference [16]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Bending Loading:

References [16, 17, 18]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Bearing Loading:

References [16, 19]

Angle used for the C Dimension: 10°

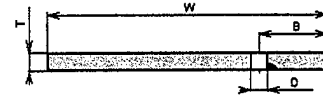
Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Offset Correction:



The solution for an offset (non-centered hole) uses the centered hole solution in AFGROW with the width adjusted to be equal to twice the distance from the center of the hole to the right edge (2B). AFGROW now includes an offset correction for a crack growing to the near edge ($B < W/2$) and an offset correction for a crack growing to the far edge ($B > W/2$). The offset corrections are given below:

For $B < W/2$:

$$F_{offset} = \frac{\sin \left(\sqrt{\frac{a}{t}} \left(\frac{D+c}{B-c/2} \right) \left(\frac{W-2B}{W} \right) \right)}{\sqrt{\frac{a}{t}} \left(\frac{D+c}{B-c/2} \right) \left(\frac{W-2B}{W} \right)} \left(1 - \left(\frac{c}{(B-D/2)} \right)^{12} \right)^{\frac{D}{2B}} \quad \text{Reference [20]}$$

This solution is valid for the following dimensions:

$$\left(\frac{D+c}{2B-c} \right) \leq 0.7$$

The solution tends to be conservative when the limit is exceeded, but the divergence is not excessive. The conservatism is normally within 1 to 3 percent until:

$$\left(\frac{D+c}{2B-c} \right) > 0.8$$

For $B > W/2$:

This correction is more complex than the previous case since the stress intensity factor may be affected by the proximity of the hole to the edge of the plate as well as the fact that the crack is growing to the far edge of the plate. The offset correction is given below:

$$F_{offset} = F_{AHFB} F_{B/W}$$

$$F_{AHFB} = 1 + \frac{\sqrt{\sec \left(\frac{\pi D}{14} \left(\frac{2}{W-B} + \frac{1.5}{B} \right) \right)} - 1}{\left[1 + 0.21 \sin \left(8 \tan^{-1} \left(\left(\frac{2B-W}{W} \right)^{0.9} \right) \right) \right]} \quad \text{Reference [21]}$$

Note: The above equation has been modified to reflect the definition of the parameter, B, used by AFGROW for this geometry.

The factor (F_{AHFB}) accounts for the effect of the proximity of the hole to the edge of the plate.

$$F_{B/W} = 1 + \left(F_{\max} \sin \left(\pi \tanh \left(2\delta^{1.1} + (1.18\delta)^7 \right) \right) \right) \quad \text{Reference [22]}$$

Where:

$$\delta = \sqrt{\frac{a}{t}} \left(\frac{D+c}{2B-c} \right)$$

$$F_{\max} = 0.5 e^{-(10\gamma + 4.2\gamma^2 + (3\gamma)^{14})}$$

$$\gamma = 1 - \frac{B}{W}$$

The factor ($F_{B/W}$) adjusts the offset correction as a function of the ratio of the offset to the plate width. This empirical curve fit was made using finite element results for a single through cracked hole. It is assumed that this correction is also valid for part through flaws. A sample beta solution is shown below in Figure 49.

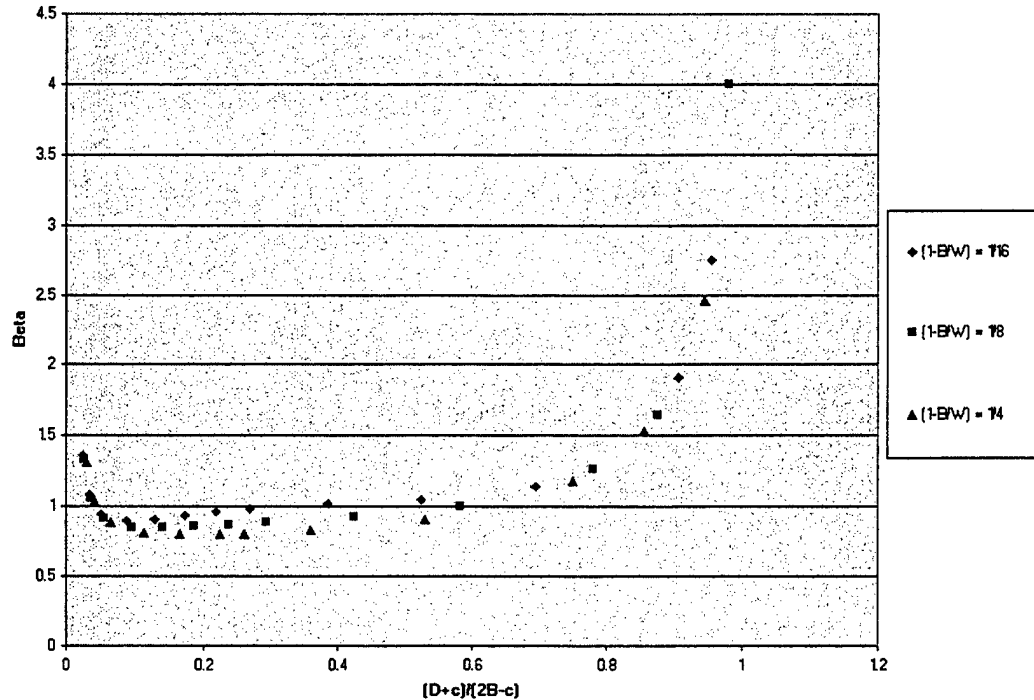
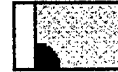


Figure 49: Sample Beta Solutions for an Offset Hole, $B > W/2$

3.2.3.1.6 Single Corner Crack at a Semi-Circular Notch (Application Defined)



Tension Loading:

Reference [23]

Angle used for the C Dimension: 2.5°

Angle used for the A Dimension: 87°

This solution is valid for the following dimensions:

$$0 < a/t < 1.0$$

$$0.2 < a/c < 2$$

$$1 < r/t < 2.0$$

$$(r+c)/w < 0.5$$

$$r/w = 1/16 \rightarrow K_t = 3.17$$

Where, r is the notch radius

3.2.3.1.7 Single Surface Crack at Hole (Application Defined)



Tension Loading:

Reference [16]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Bearing Loading:

References [16, 19]

Angle used for the C Dimension: 10°

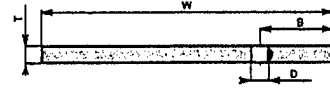
Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Offset Correction:



The solution for an offset (non-centered hole) uses the centered hole solution in AFGROW with the width adjusted to be equal to twice the distance from the center of the hole to the right edge ($2B$). AFGROW now includes an offset correction for a crack growing to the near edge ($B < W/2$) and an offset correction for a crack growing to the far edge ($B > W/2$). The offset corrections are given below:

For $B < W/2$:

$$F_{offset} = \frac{\sin \left(\sqrt{\frac{a}{t}} \left(\frac{D+c}{B-c/2} \right) \left(\frac{W-2B}{W} \right) \right)}{\sqrt{\frac{a}{t}} \left(\frac{D+c}{B-c/2} \right) \left(\frac{W-2B}{W} \right)} \left(1 - \left(\frac{c}{(B-D/2)} \right)^{12} \right)^{\frac{D}{2B}} \quad \text{Reference [20]}$$

This solution is valid for the following dimensions:

$$\left(\frac{D+c}{2B-c} \right) \leq 0.7$$

The solution tends to be conservative when the limit is exceeded, but the divergence is not excessive. The conservatism is normally within 1 to 3 percent until:

$$\left(\frac{D+c}{2B-c} \right) > 0.8$$

For $B > W/2$:

This correction is more complex than the previous case since the stress intensity factor may be affected by the proximity of the hole to the edge of the plate as well as the fact that the crack is growing to the far edge of the plate. The offset correction is given below:

$$F_{offset} = F_{AHFB} F_{B/W}$$

$$F_{AHFB} = 1 + \frac{\sqrt{\sec\left(\frac{\pi D}{14} \left(\frac{2}{W-B} + \frac{1.5}{B}\right)\right) - 1}}{\left[1 + 0.21 \sin\left(8 \tan^{-1}\left(\left(\frac{2B-W}{W}\right)^{0.9}\right)\right)\right]} \quad \text{Reference [21]}$$

Note: The above equation has been modified to reflect the definition of the parameter, B , used by AFGROW for this geometry.

The factor (F_{AHFB}) accounts for the effect of the proximity of the hole to the edge of the plate.

$$F_{B/W} = 1 + \left(F_{max} \sin\left(\pi \tanh\left(2\delta^{1.1} + (1.18\delta)^7\right)\right)\right) \quad \text{Reference [22]}$$

Where:

$$\delta = \sqrt{\frac{a}{t} \left(\frac{D+c}{2B-c}\right)}$$

$$F_{max} = 0.5 e^{-(10\gamma + 4.2\gamma^2 + (3\gamma)^{14})}$$

$$\gamma = 1 - \frac{B}{W}$$

The factor ($F_{B/W}$) adjusts the offset correction as a function of the ratio of the offset to the plate width. This empirical curve fit was made using finite element results for a single through cracked hole. It is assumed that this correction is also valid for part through flaws. A sample beta solution is shown in Figure 49.

3.2.3.1.8 Single Surface Crack at a Semi-Circular Notch (Application Defined)



Tension Loading:

Reference [23]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 85°

This solution is valid for the following dimensions:

$$0 < a/t < 0.5$$

$$0.2 < a/c < 2$$

$$1 < r/t < 3.5$$

$$(r+c)/w < 0.5$$

$$r/w = 1/16 \rightarrow K_t = 3.17$$

Where, r is the notch radius

3.2.3.1.9 Double Corner Crack at Hole (Application Defined)



Tension Loading:

Reference [16]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Bending Loading:

References [16, 17, and 18]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Bearing Loading:

References [16, 19]

Angle used for the C Dimension: 10°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

3.2.3.1.10 Double Surface Crack at Hole (Application Defined)



Tension Loading:

Reference [16]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Bearing Loading:

References [16, 19]

Angle used for the C Dimension: 10°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

3.2.3.1.11 Single Edge Corner Crack (Application Defined)



Tension Loading:

Reference [16]

Angle used for the C Dimension: 5°

Angle used for the A Dimension: 83°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

3.2.3.1.12 Single Corner Crack in Lug (Application Defined)



Bearing Loading:

Reference [16]

Combination and Empirical Fits of:

References [24, 25]

Angle used for the C Dimension: 10°

Angle used for the A Dimension: 80°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

3.2.3.1.13 Part Through Crack in Pipe (Application Defined)



Tension Loading:

Reference [26]

Angle used for the C Dimension: 0°

Angle used for the A Dimension: 90°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

Bending Loading:

Reference [26]

Angle used for the C Dimension: 0°

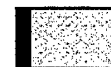
Angle used for the A Dimension: 90°

This solution is valid for the following dimensions:

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 2.0$$

3.2.3.1.14 Through Crack (User Defined)




This model is used when a user has an existing stress intensity factor solution (in the form of a beta table) for any 1-D crack, which may be described with one length dimension (1-D) to input in AFGROW.

The geometric beta values are NOT calculated by AFGROW, but are merely interpolated from a one-dimensional user defined table of beta values. Users must supply beta values at various crack lengths so that the appropriate value at a given crack length may be interpolated. This model is shown as an edge cracked plate in the animation frame. The

representation of the model is merely meant to indicate the one-dimensional nature of the crack. It was not possible to create representations of all possible geometries that may be modeled using user defined beta factors

For the [c] crack length dimension: $K = \sigma \sqrt{\pi c} \beta(c)$

Once this model is selected, AFGROW will add a user input beta icon, , in the AFGROW toolbar (if active). A blinking indication will also be activated in the status view of the main frame window indicating that user-defined beta information is required. Users may choose any external source to calculate stress intensity factors and convert them to beta values. Details of the through crack (1-D) user-defined beta option are given in section 3.2.7.1.

3.2.3.1.15 Center Through Crack (Application Defined)



Tension Loading:

$$\text{Beta} = 1.0 - 0.025 \left(\frac{2C}{W} \right)^2 + 0.06 \left(\frac{2C}{W} \right)^4 \sqrt{\sec(\pi C/W)}$$

Reference [27]

This solution is valid for the following dimensions:

$$0 < C/W \leq 0.5$$

This solution is within 0.1% for all crack lengths

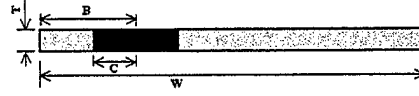
Bending Loading:

$$\text{Beta} = \frac{2}{3} \text{Beta (Tension)}$$

It is important to be very clear that there is no way to provide a true solution for the out-of-plane bending case since the actual stress intensity value will vary through the thickness. The two thirds value is simply being used to provide a solution for the straight through crack that provides reasonable continuity with the bending solution for the c-dimension of the part-through (surface) crack. This solution is required to allow users to model bending for the surface crack case since the surface crack may transition to become a through crack. The most accurate way to model this case is to use an oblique through crack solution, which accounts for the changes in the stress intensity solution through the thickness. Unfortunately, no oblique internal crack solutions were found that are valid for the full range of crack shapes required. A partial oblique internal through crack solution was found [28] that could be used to provide a transition from a surface to a straight through crack. This option is available in the surface crack dialog (see section

3.2.3.1.2), but is NOT available for the through crack case. The oblique through crack solution does not cover the full range of possible oblique shapes. If this option is selected for the surface crack case, transition to a straight through crack will occur as soon as the crack shape exceeds the limits of the existing oblique solution.

Offset Correction:



The stress intensity solution for the offset internal through crack must be calculated at each crack tip. The offset case is non-symmetric, and the stress intensity values of each crack tip will be different. The offset parameter, B, is defined as the distance between the nearest plate edge and the center of the through crack. AFGROW measures this distance from the left edge of the plate and B must be less than one half of the plate width. Any offset case may be modeled in this manner. An offset crack on the right side of the plate will be on the left side if the plate is rotated 180 degrees.

The solution for the crack tip closest to the edge of the plate is:

Reference [29]

$$\text{Beta} = \sqrt{\sec\left(\frac{\pi\lambda}{2}\right) \frac{\sin\left(2\lambda - \frac{4C_{eq}}{W}\right)}{2\lambda - \frac{4C_{eq}}{W}}}$$

$$\text{Where: } \lambda = \frac{C_{eq}}{B_{eq}}$$

C_{eq} = current half crack length

B_{eq} = current distance from the near plate edge to the crack center

The solution for the crack tip furthest from the plate edge is:

Reference [30]

$$\text{Beta} = 1 + \frac{\sqrt{\sec\left(\frac{1}{7}\left(2\pi\lambda + \frac{3\pi C_{eq}}{2(W - B_{eq})}\right)\right) - 1}}{\left[1 + 0.21 \sin\left(8 \tan^{-1}\left(\frac{\pi\lambda - \frac{\pi C_{eq}}{(W - B_{eq})}}{\pi\lambda + \frac{\pi C_{eq}}{(W - B_{eq})}}\right)^{0.9}\right)\right]}$$

Where: $\lambda = \frac{C_{eq}}{B_{eq}}$

C_{eq} = current half crack length

B_{eq} = current distance from the near plate edge to the crack center

3.2.3.1.16 Single Through Crack at Hole (Application Defined)



AFGROW now allows for either straight or oblique through cracks to be analyzed for this geometry. As the name implies, straight through-the-thickness cracks are assumed to be one-dimensional cracks of constant length (C) through the thickness of a component (see Figure 50).

Enter crack dimensions

Crack Length -C- Direction: 0.15

☐ Oblique through crack

Figure 50: Straight Through-the-Thickness Cracks

Oblique cracks are assumed to be elliptic in shape and are NOT of constant length through the thickness (see Figure 51).

Enter crack dimensions

Crack Length -C- Direction: 0.15

Crack Length -Ct- Direction: 0.05

☒ Oblique through crack

Figure 51: Oblique Through-the-Thickness Cracks

Tension Loading:

Infinite Plate Solution:

$$\text{Beta} = 0.7071 + 0.7548 \left(\frac{R}{R+C} \right) + 0.3415 \left(\frac{R}{R+C} \right)^2 + 0.642 \left(\frac{R}{R+C} \right)^3 + 0.9196 \left(\frac{R}{R+C} \right)^4$$

Reference [31]

Finite Width Correction:

$$F_w = \sqrt{\sec\left(\frac{\pi R}{W}\right) \sec\left(\frac{\pi (R + C/2)}{W - C}\right)}$$

The finite width correction was taken from reference 16, Equation 46 with a/t set to 1.0.

This solution is valid for the following dimensions:

$$0 < C/R \leq \text{infinite}$$

$$\frac{R + C/2}{W - C} < 0.5$$

Bending Loading:

Infinite Plate Solution:

Reference [32]

Note: Equation 9 (single crack solution) was used from this reference - The actual beta value was obtained by dividing by $\sqrt{\pi}$ since the reference left that value out of the calculation of stress intensity.

$$\text{Beta} = \sqrt{\frac{1}{2\pi}} \left(\frac{C/R + 2}{C/R + 1} \right)^{1.5} F_c F_w$$

The factor, F_c , was added to correct equation 9 (which is a shear stress solution) to match the bending data provided in the above reference for a Poisson's ratio of 1/3. The error for any C/R was determined to be less than 1 percent for any C/R (for most values the error was MUCH less than 1 percent) according to the above reference. The difference between the data at Poisson's ratios of 1/3 and 1/4 is very small - other solutions use a correction for Poisson's ratio that is in great disagreement with this reference.

$$F_c = 0.9 + 0.083(1 - 10^{-0.046(C/R)}) + 0.017(1 - 10^{-3.0(C/R)})$$

Finite Width Correction:

$$F_w = \sqrt{\sec\left(\frac{\pi R}{W}\right) \sec\left(\frac{\pi (R + C/2)}{W - C}\right)}$$

The finite width correction was taken from reference 17, Equation 46 with a/t set to 1.0.

This solution is valid for the following dimensions:

$$0 < C/R \leq \text{infinite}$$

$$\frac{R + C/2}{W - C} < 0.5$$

Bearing Loading:

$$\text{Beta} = F_4 * F_w$$

Infinite Plate Solution:

The infinite plate solution is interpolated from the tabular solution [19] shown below.

C/R	0.0	0.25	0.5	1.0	2.0	3.0	4.0	5.0	7.5
F4	0.95	0.6	0.429	0.286	0.177	0.13	0.107	0.095	0.095

Finite Width Correction:

$$F_w = \sqrt{\sec\left(\frac{\pi(R + C)}{W}\right)}$$

Reference [33]

This solution is valid for the following dimensions:

$$0 < C/R \leq 7.5$$

$$(R + C)/W < 0.5$$

Oblique Through-the-Thickness Cracks

Dr. Scott Fawaz developed the finite element based oblique crack solutions for tension, bending, and bearing loading conditions [34, 35]. See Figure 51 for a description of the input requirements for the oblique crack.

The crack geometry is defined in Figure 52:

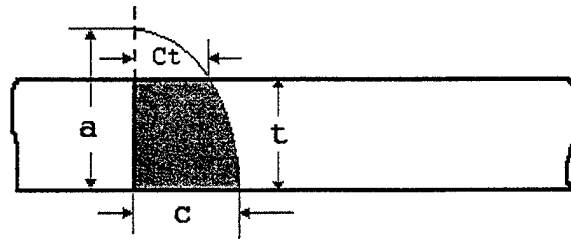


Figure 52: Oblique Through-the-Thickness Crack Geometry

The virtual corner crack is a quarter ellipse with the center at what would be the crack origin of a corner crack that has transitioned to an oblique through-the-thickness flaw at a hole in an infinite plate. The elliptical axes are defined by the A and C dimensions. While the A dimension is not input by the user, it is calculated from the [C, Ct, and t] dimensions which are input by the user. Dr. Fawaz's finite element solutions were calculated for the following range of dimensions:

$a/c = 0.2, 0.3, 0.4, 0.6, 1.0, 2.0, 5.0, \text{ and } 10.0$

$a/t = 1.05, 1.07, 1.09, 1.13, 1.17, 1.21, 2.0, 5.0, \text{ and } 10.0$

$R/t = 0.5, 1.0, \text{ and } 2.0$ - where R is the hole radius

Beta factors for each case were then calculated for the [C] and [Ct] dimensions as follows:

$$\text{Beta} = \frac{K}{\sigma \sqrt{\pi x}} ; \text{ Where } x \text{ is the appropriate crack length}$$

In this case, crack length is the C or Ct dimension. AFGROW uses a cubic spline interpolation technique to determine the appropriate beta value during crack growth life prediction. The following rules are used in AFGROW when the oblique through crack option is selected:

- No extrapolation is made beyond the bounds of the finite element cases
- If a/c , or a/t goes below the limit of the finite element cases, the value will be held at that limit
- If R/t is beyond the limits, it will be maintained at the nearest limit value
- If a/c , or a/t goes above the limits, the crack will be transitioned to a straight through-the-thickness crack of length [C]

Finite Width Correction:

$$F_w = \sqrt{\sec\left(\frac{\pi R}{W}\right) \sec\left(\frac{\pi (R + C/2)}{W - C}\right)}$$

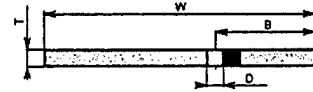
The finite width correction was taken from Reference 17, Equation 46 with a/t set to 1.0.

This solution is valid for the following dimensions:

$$\frac{R + C/2}{W - C} < 0.5$$

The Fawaz solutions were calculated for the double cracked hole case and were corrected for the single crack case by the Shah correction as follows:

$$\text{Beta (single crack)} = \text{Beta (double crack)} * \sqrt{\frac{8R + \pi C}{8R + 2\pi C}}$$



Offset Correction:

The solution for an offset (non-centered hole) uses the centered hole solution in AFGROW with the width adjusted to be equal to twice the distance from the center of the hole to the right edge ($2B$). AFGROW now includes an offset correction for a crack growing to the near edge ($B < W/2$) and an offset correction for a crack growing to the far edge ($B > W/2$). The offset corrections are given below:

For $B < W/2$:

$$F_{offset} = \frac{\sin\left(\left(\frac{D+c}{B-c/2}\right)\left(\frac{W-2B}{W}\right)\right)}{\left(\frac{D+c}{B-c/2}\right)\left(\frac{W-2B}{W}\right)} \left(1 - \left(\frac{c}{(B-D/2)}\right)^{12}\right)^{\frac{D}{2B}} \quad \text{Reference [20]}$$

This solution is valid for the following dimensions:

$$\left(\frac{D+c}{2B-c}\right) \leq 0.7$$

The solution tends to be conservative when the limit is exceeded, but the divergence is not excessive. The conservatism is normally within 1 to 3 percent until:

$$\left(\frac{D+c}{2B-c} \right) > 0.8$$

For $B > W/2$:

This correction is more complex than the previous case since the stress intensity factor may be affected by the proximity of the hole to the edge of the plate as well as the fact that the crack is growing to the far edge of the plate. The offset correction is given below:

$$F_{\text{offset}} = F_{\text{AHFB}} F_{B/W}$$

$$F_{\text{AHFB}} = 1 + \frac{\sqrt{\sec\left(\frac{\pi D}{14} \left(\frac{2}{W-B} + \frac{1.5}{B} \right)\right) - 1}}{\left[1 + 0.21 \sin\left(8 \tan^{-1}\left(\left(\frac{2B-W}{W} \right)^{0.9} \right) \right) \right]} \quad \text{Reference [21]}$$

Note: The above equation has been modified to reflect the definition of the parameter, B , used by AFGROW for this geometry.

The factor (F_{AHFB}) accounts for the effect of the proximity of the hole to the edge of the plate.

$$F_{B/W} = 1 + \left(F_{\text{max}} \sin\left(\pi \tanh\left(2\delta^{1.1} + (1.18\delta)^7 \right) \right) \right) \quad \text{Reference [22]}$$

Where:

$$\delta = \frac{D+c}{2B-c}$$

$$F_{\text{max}} = 0.5 e^{-(10\gamma + 4.2\gamma^2 + (3\gamma)^{14})}$$

$$\gamma = 1 - \frac{B}{W}$$

The factor ($F_{B/W}$) adjusts the offset correction as a function of the ratio of the offset to the plate width. This empirical curve fit was made using finite element results for a single through cracked hole. A sample beta solution is shown in Figure 49.

3.2.3.1.17 Double Through Crack at Hole (Application Defined)



AFGROW now allows for either straight or oblique through cracks to be analyzed for this geometry. As the name implies, straight through-the-thickness cracks are assumed to be one-dimensional cracks of constant length (C) through the thickness of a component (see Figure 50, section 3.2.3.1.16). Oblique cracks are assumed to be elliptic in shape and are NOT of constant length through the thickness (see Figure 51, section 3.2.3.1.16).

Tension Loading:

Infinite Plate Solution:

$$\text{Beta} = 0.5 \left(3.0 - \frac{C}{R+C} \right) \left(1.0 + 1.243 \left(1.0 - \frac{C}{R+C} \right)^3 \right) * F_w$$

Reference [36]

Finite Width Correction:

$$F_w = \sqrt{\sec\left(\frac{\pi R}{W}\right) \sec\left(\frac{\pi (R+C)}{W}\right)}$$

The finite width correction was taken from reference 16, Equation 46 with a/t set to 1.0.

This solution is valid for the following dimensions:

$$0 < C/R \leq \text{infinite}$$

$$\frac{R+C}{W} < 0.5$$

Bending Loading:

The double cracked hole solutions are corrected from the single-cracked solutions using the Shah Correction (with a/t set = 1.0)

$$\text{Beta (double crack)} = \text{Beta (single crack)} * \sqrt{\frac{8R + 2\pi C}{8R + \pi C}}$$

Infinite Plate Solution:

Reference [32]

Note: Equation 9 (single crack solution) was used from this reference - The actual beta value was obtained by dividing by $\sqrt{\pi}$ since the reference left that value out of the calculation of stress intensity.

$$\text{Beta} = \sqrt{\frac{1}{2\pi} \left(\frac{C/R+2}{C/R+1} \right)^{1.5} \frac{8R+2\pi C}{8R+\pi C}} F_c F_w$$

The factor, F_c , was added to correct equation 9 (which is a shear stress solution) to match the bending data provided in the above reference for a Poisson's ratio of 1/3. The error for any C/R was determined to be less than 1 percent for any C/R (for most values the error was MUCH less than 1 percent) according to the above reference. The difference between the data at Poisson's ratios of 1/3 and 1/4 are very small - other solutions use a correction for Poisson's ratio that is in great disagreement with this reference.

$$F_c = 0.9 + 0.083(1 - 10^{-0.046(C/R)}) + 0.017(1 - 10^{-3.0(C/R)})$$

Finite Width Correction:

$$F_w = \sqrt{\sec\left(\frac{\pi R}{W}\right) \sec\left(\frac{\pi(R+C)}{W}\right)}$$

The finite width correction was taken from Reference 17, Equation 46 with a/t set to 1.0.

This solution is valid for the following dimensions:

$$0 < C/R \leq \text{infinite}$$

$$\frac{R+C}{W} < 0.5$$

Bearing Loading:

$$\text{Beta} = F_3 * F_w$$

Infinite Plate Solution:

The infinite plate solution is interpolated from the tabular solution based on the following reference.

Reference [19]

C/R	0.0	0.25	0.5	0.75	1.0	2.0	3.0	4.0	5.0	7.5	10.0
F ₃	0.84	0.575	0.455	0.380	0.325	0.22	0.173	0.143	0.125	0.1	0.1

Finite Width Correction:

$$F_w = \sqrt{\sec\left(\frac{\pi(R+C)}{W}\right)}$$

Reference [33]

This solution is valid for the following dimensions:

$$0 < C/R \leq 10$$

$$(R + C)/W < 0.5$$

Oblique Through-the-Thickness Cracks:

Dr. Scott Fawaz developed the finite element based oblique crack solutions for tension, bending, and bearing loading conditions [34, 35].

The virtual corner crack is a quarter ellipse with the center at what would be the crack origin of a corner crack that has transitioned to an oblique through-the-thickness flaw at a hole in an infinite plate (see Figure 52, section 3.2.3.1.16). The elliptical axes are defined by the A and C dimensions. While the A dimension is not input by the user, it is calculated from the [C, Ct, and t] dimensions which are input by the user. Dr. Fawaz's finite element solutions were calculated for the following range of dimensions:

$$a/c = 0.2, 0.3, 0.4, 0.6, 1.0, 2.0, 5.0, \text{ and } 10.0$$

$$a/t = 1.05, 1.07, 1.09, 1.13, 1.17, 1.21, 2.0, 5.0, \text{ and } 10.0$$

$$R/t = 0.5, 1.0, \text{ and } 2.0 - \text{where } R \text{ is the hole radius}$$

Beta factors for each case were then calculated for the [C] and [Ct] dimensions as follows:

$$\text{Beta} = \frac{K}{\sigma \sqrt{\pi x}} ; \text{Where } x \text{ is the appropriate crack length}$$

In this case, crack length is the C or Ct dimension. AFGROW uses a cubic spline interpolation technique to determine the appropriate beta value during crack growth life prediction. The following rules are used in AFGROW when the oblique through crack option is selected:

- No extrapolation is made beyond the bounds of the finite element cases
- If a/c, or a/t goes below the limit of the finite element cases, the value will be held at that limit
- If R/t is beyond the limits, it will be maintained at the nearest limit value
- If a/c, or a/t goes above the limits, the crack will be transitioned to a straight through-the-thickness crack of length [C]

Finite Width Correction:

$$F_w = \sqrt{\sec\left(\frac{\pi R}{W}\right) \sec\left(\frac{\pi(R+C)}{W}\right)}$$

The finite width correction was taken from reference 16, Equation 46 with a/t set to 1.0.

This solution is valid for the following dimensions:

$$\frac{R+C}{W} < 0.5$$

3.2.3.1.18 Through Crack at a Semi-Circular Notch (Application Defined)



Tension Loading:

Reference [23]

This solution is valid for the following dimensions:

$$(r+c)/w < 0.8$$

$$r/w = 1/16 \rightarrow K_t = 3.17$$

Where, r is the notch radius

3.2.3.1.19 Single Edge Through Crack (Application Defined)



Tension Loading:

The standard solution for the edge cracked case accounts for in-plane bending caused by the specimen geometry as the crack grows. The specimen is assumed to be remotely pin loaded so there is no constraint to the in-plane bending as the crack grows.

$$\text{Beta} = \frac{\left(0.752 + 2.02(C/W) + 0.37 \left(1 - \sin\left(\frac{\pi C}{2W} \right) \right)^3 \right)}{\cos\left(\frac{\pi C}{2W} \right)} \sqrt{\frac{2W}{\pi C} \tan\left(\frac{\pi C}{2W} \right)}$$

Reference [37]

This solution is valid for the following dimensions:

$$0 < C/W < 1.0$$

This solution is within 0.5% for all crack lengths

AFGROW now includes an option to perform life predictions for edge crack cases where the in-plane bending is constrained (see Figure 53).

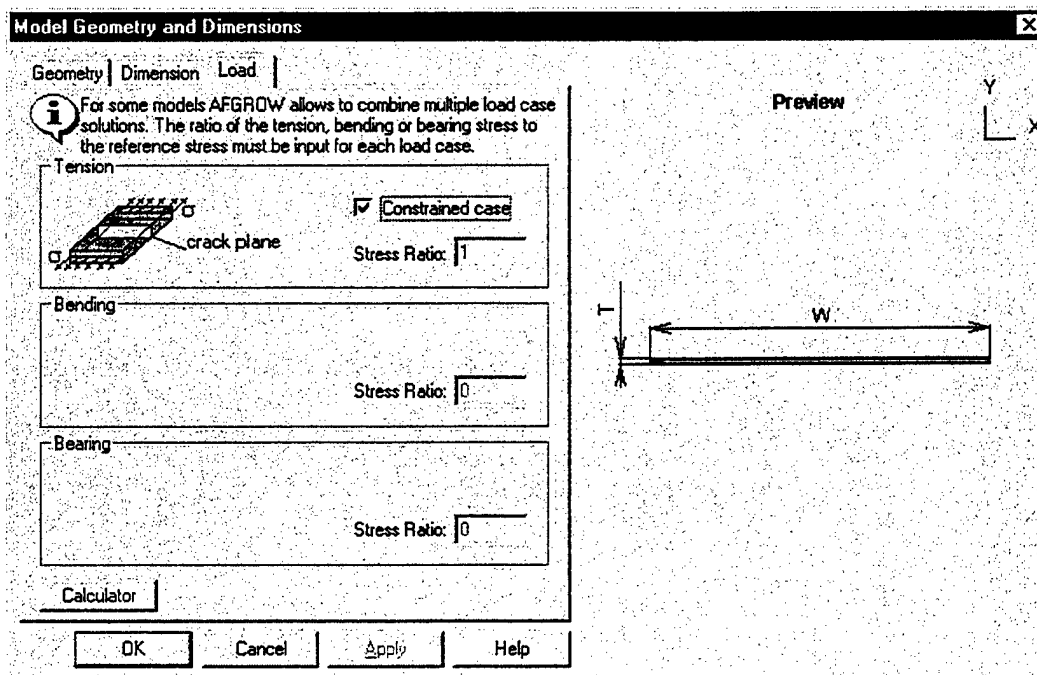


Figure 53: In-Plane Bending Constraint Option for the Edge Cracked Plate

To constrain (eliminate) the in-plane bending contribution from the single edge cracked plate, select the option for the constrained case in the load tab for the edge crack model as shown in Figure 53. The constrained solution was determined from numerous finite element models using FRANC2D/L [38].

The easiest way to eliminate in-plane bending from the edge crack case is to apply a uniform displacement to the finite element model. This method can be used to determine the stress intensity factor for a specific case. To be applicable to all edge crack cases, this solution should be in the form of a beta factor table.

$$Beta = \frac{K}{\sigma \sqrt{\pi c}}; \text{ Where } c \text{ is the crack length}$$

If the stress intensity factor is known for a given edge crack case, the beta factor may be determined if the remote applied stress, σ , is known. The remote stress for the uniform displacement model can be extracted from the finite element model for relatively short cracks. When longer crack lengths are modeled it becomes more difficult to determine the equivalent remote stress since the longer cracks cause large changes in the internal stress distribution. Applying a uniformly distributed unit stress to the plate and constraining the displacement (normal to the applied stress) of the mid-plane nodes in the upper and lower portions of the plate model solved this problem. It was important to constrain only the mid-plane nodes to maintain a uniform stress field through the plate width. The nodes in the area of the crack plane were NOT constrained. The beta values obtained using this approach were accurate within 0.1 percent of the uniform displacement method for the shorter crack lengths (where they could be compared). In addition, the stress distributions were in very good agreement for the long crack cases.

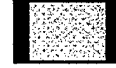
The beta solution for an edge crack in a semi-infinite plate is known to be equal to 1.122. This is true for both the constrained and unconstrained cases. The solution for the finite width cases is:

$$Beta = 1.122 * F_w; \text{ Where, } F_w \text{ is the finite width correction}$$

The finite width correction is simply a function of the ratio of the crack length to the plate width (c/w). This was verified by modeling various plate widths and comparing the betas at given c/w values. The resulting beta table is used in AFGROW to determine beta values when the in-plane bending constraint option is selected.

C/W	Beta
0	1.122
0.01	1.124
0.025	1.127
0.05	1.132
0.1	1.165
0.15	1.185
0.2	1.23
0.3	1.32
0.4	1.46
0.5	1.606
0.625	1.835
0.75	2.156
0.8	2.327
0.8333	2.499
0.875	2.789
0.9	3.005
0.916667	3.244
0.95	3.933
1	5.36

3.2.3.1.20 Double Edge Through Crack (Application Defined)



Tension Loading:

$$\text{Beta} = \left(1.0 + 0.122 \cos^4 \left(\frac{\pi C}{W} \right) \right) \sqrt{\frac{W}{\pi C} \tan \left(\frac{\pi C}{W} \right)}$$

Reference [39]

This solution is valid for the following dimensions:

$$0 < C/W < 0.5$$

This solution is within 0.5% for all crack lengths

3.2.3.1.21 WOL/CT Specimen (Application Defined)



Note: The loading for this geometry is applied as pin loads through bolt holes in the specimen. Therefore, the input tension (stress) value is not really a stress value, but is LOAD. When using this geometry, the user must input the applied LOAD instead of stress. The diagram in the loads tab indicates a remote stress input, but this is because all other geometries use remote stress as the input for the tension case. This geometry is an exception to that rule.

Tension Loading:

Reference [39]

This solution is valid for the following dimensions:

$$0.2 < C/W \leq 0.975$$

This solution is within 0.5% for all crack lengths in the range above.

3.2.3.1.22 Single Edge Crack in Lug (Application Defined)



Bearing Loading:

Combination and Empirical Fits of:

References [24, 25]

3.2.3.1.23 Rod (Application Defined)



Tension Loading:

Reference [41]

Bending Loading:

Reference [41]

3.2.3.1.24 Through Crack in Pipe (Application Defined)



Tension Loading:

Reference [42]

Bending Loading:

Reference [42]

3.2.3.2 Weight Function Stress Intensity Solutions

The weight function solutions [7] in AFGROW were provided under sub-contract to AS&M by Prof. G. Glinka, University of Waterloo, CA. Professor Glinka's solutions were translated to the C/C++ language and adapted for use in AFGROW.

3.2.3.2.1 Center Semi-Elliptical Surface Crack (Glinka's Weight Function)



This solution is valid for the following dimensions:

$$0 < a/t \leq 0.8$$

$$0 < a/c \leq 2.0$$

3.2.3.2.2 Single Corner Crack (Glinka's Weight Function)



This solution is valid for the following dimensions:

$$0 < a/t \leq 0.8$$

$$0.2 \leq a/c \leq 1.0$$

3.2.3.2.3 Internal Axial Crack in Thick Pipe (Glinka's Weight Function)



This solution is valid for the following dimensions:

$$1.1 \leq R_o/R_i \leq 2.0 ; \text{ Where } R_o : \text{ Outside Pipe Radius, } R_i : \text{ Inside Pipe Radius}$$

$$0 < a/t \leq 0.8$$

$$0.2 \leq a/c \leq 1.0$$

3.2.3.2.4 External Axial Crack in Thick Pipe (Glinka's Weight Function)



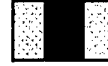
This solution is valid for the following dimensions:

$$1.1 \leq R_o/R \leq 2.0 ; \text{ Where } R_o : \text{ Outside Pipe Radius, } R_i : \text{ Inside Pipe Radius}$$

$$0 < a/t \leq 1.0$$

$$0.2 \leq a/c \leq 1.0$$

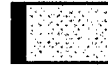
3.2.3.2.5 Center Through Crack (Glinka's Weight Function)



This solution is valid for the following dimensions:

$$0 < c/w < 0.45$$

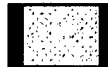
3.2.3.2.6 Single Edge Through Crack (Glinka's Weight Function)



This solution is valid for the following dimensions:

$$0 < c/w < 0.9$$

3.2.3.2.7 Double Edge Through Crack (Glinka's Weight Function)



This solution is valid for the following dimensions:

$$0 < c/w < 0.45$$

3.2.3.2.8 Radial Edge Crack in Disc (Glinka's Weight Function)



This solution is valid for the following dimensions:

$$0 < c/Dia. < 0.9$$

3.2.3.2.9 Axial Through Crack in Thick Pipe (Glinka's Weight Function)



This solution is valid for the following dimensions:

$$1.1 \leq R_o/R_i \leq 2.0$$

$$0 < c/w < 0.45$$

3.2.3.3 Using the Weight Function Solutions

The 2-D solutions currently allow the input stress field to vary in the one direction only (currently the distribution in the thickness (y) direction). The details of the stress field input are given in the stress distribution dialog. When the part through the thickness cracks transition to become through-the-thickness cracks, the model is automatically changed to the appropriate 1-D case and the applicable stress distribution is used to continue the life prediction. The stress distribution in the width (x) direction is always used for 1-D cases. Certain Tips and Tricks are available to provide additional guidance in the use of the weight function solutions.

3.2.3.3.1 Weight Function Stress Distribution

The decision whether to normalize the input stress distribution is really a personal preference as long as you have a clear understanding of the relationship between the input spectrum, stress multiplication factor, and the stress distribution you plan to use. The main thing to remember is that all three values are multiplied together by AFGROW to determine the stress values at each point where you input stress (or load).

For example, to simulate a double-cracked open hole with a remote gross stress ($P/(W \cdot t)$) of 14 ksi, $R = 0$, initial crack size = 0.07 in, (from hole), the following was done:

- A normalized spectrum was used - Max Stress = 1.0
- Stress Multiplication Factor = 14
- Finite element results (FRANC2D) provided un-flawed K_t vs. crack length in the crack plane.
- Center cracked weight function model was chosen based on geometric similarity
- Open hole (0.5 in. dia.) modeled by a stress free zone
- Initial half crack length = $0.25 \text{ (radius)} + 0.07 = 0.32 \text{ in.}$

The stress distribution dialog is shown in Figure 54:

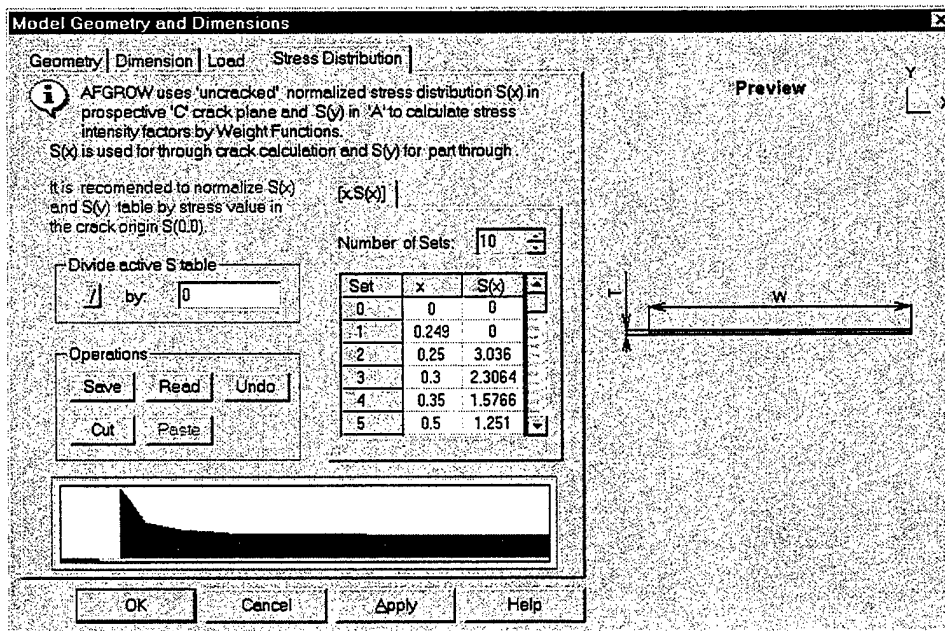


Figure 54: Weight Function Stress Distribution Dialog

AFGROW provides a tool to allow the stress values to be divided by a given number. This is especially helpful in cases where the user wants to normalize the stress values.

Since there is no weight function solution for a double cracked hole, the center-cracked case was used with a stress free area where the hole would have been located. A total of ten points were used to characterize the unflawed stress distribution in the crack plane.

The input distribution is shown in the stress distribution dialog. AFGROW accepts a maximum of 25 points to define the stress distribution. The points do not have to be equally spaced, but should be spaced such that linear interpolation between points adequately matches the desired distribution.

In order to judge the effectiveness of this approximate solution, a comparison of life prediction analyses was made between this solution and the standard double cracked hole solution (see Figure 55).

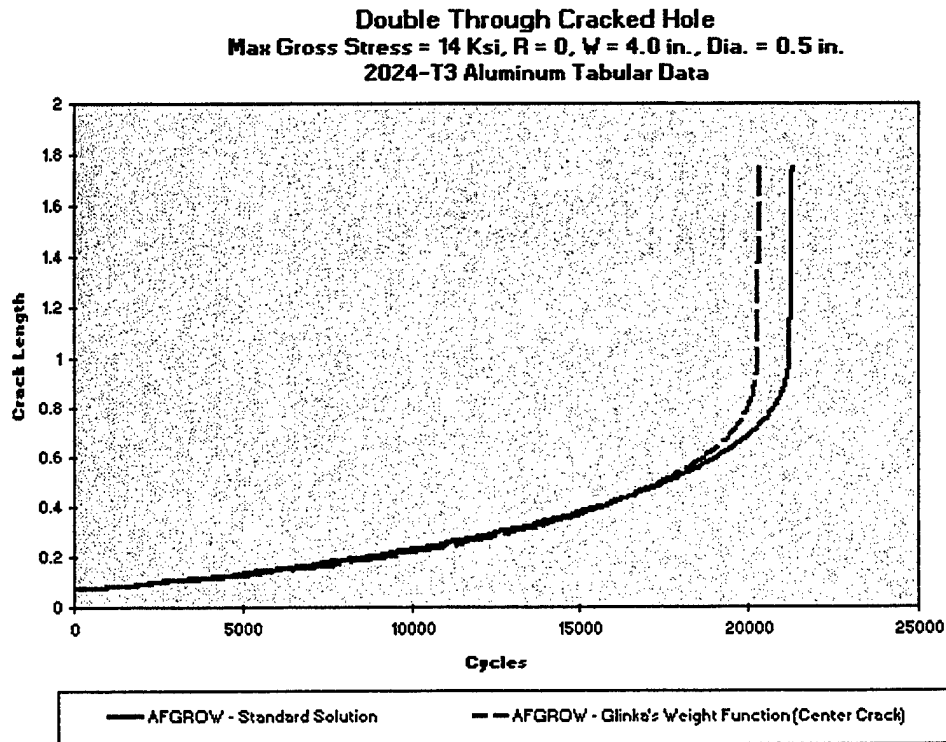


Figure 55: Comparison Between Weight Function and Standard Solutions

The weight function solution resulted in an excellent agreement in life to a certain crack length. This comparison is very sensitive to small changes in stress intensity. Hence, this approximation is excellent to a crack length of approximately 0.5 inches.

3.2.3.3.2 Weight Function Tips and Tricks

Choose the Appropriate Weight Function Model. Try to choose the model that is geometrically CLOSEST to the problem being approximated.

The current 2-D weight function solutions in AFGROW only permit the input stress distribution to vary in a single direction. Prof. Glinka's solutions for part-through cases can be adjusted to switch dimensions. At this time, only the single corner and surface crack models are available. Future releases are planned which will include additional models.

If a through crack at an edge notched specimen is being modeled, use the edge crack model, determine the unflawed stress distribution, and model the notch depth as a stress free area as was done in the example given above

Additional tips or tricks will be provided as more experience is gained working with the solutions.

3.2.3.3.3 Weight Function Verification

Comparisons between weight function and available closed-form stress intensity solutions have been made to aid in the verification of the weight function solutions. Selected weight function stress intensity models, provided by Prof. Glinka, have been compared to existing closed form solutions to demonstrate the accuracy of the weight function solutions. A copy of the stress distribution dialog is provided for each case. The results are shown below in Figure 56 and Figure 57:

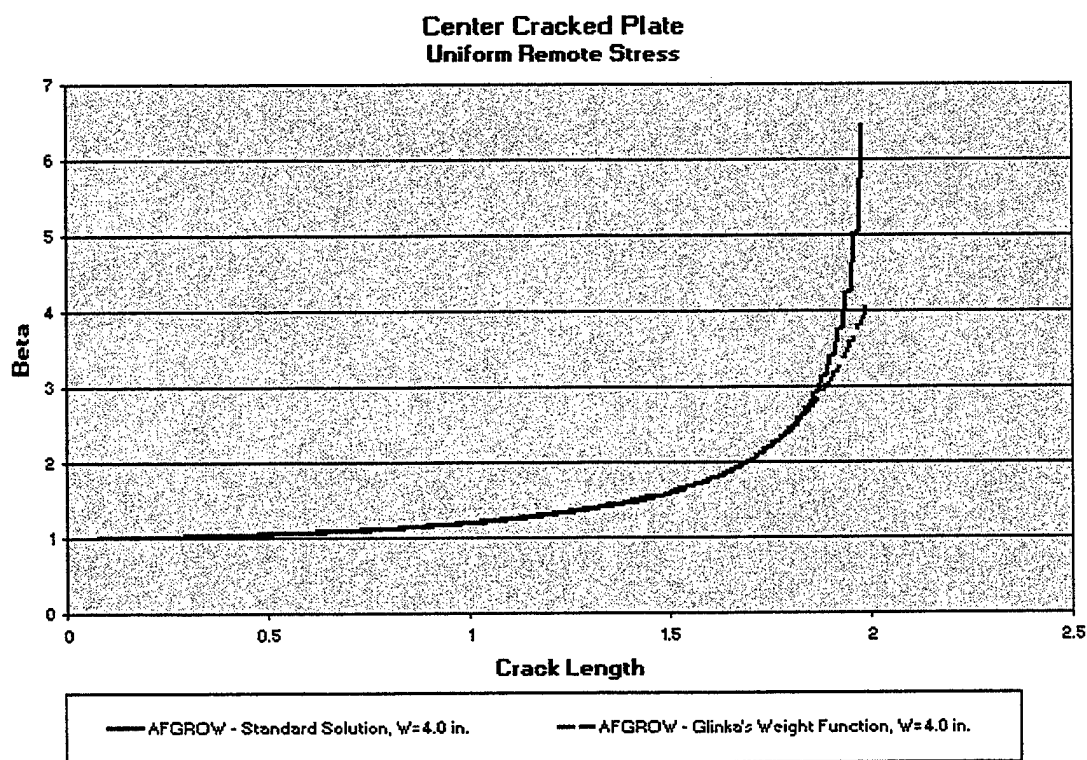


Figure 56: Center Crack Under Uniform Tensile Loading

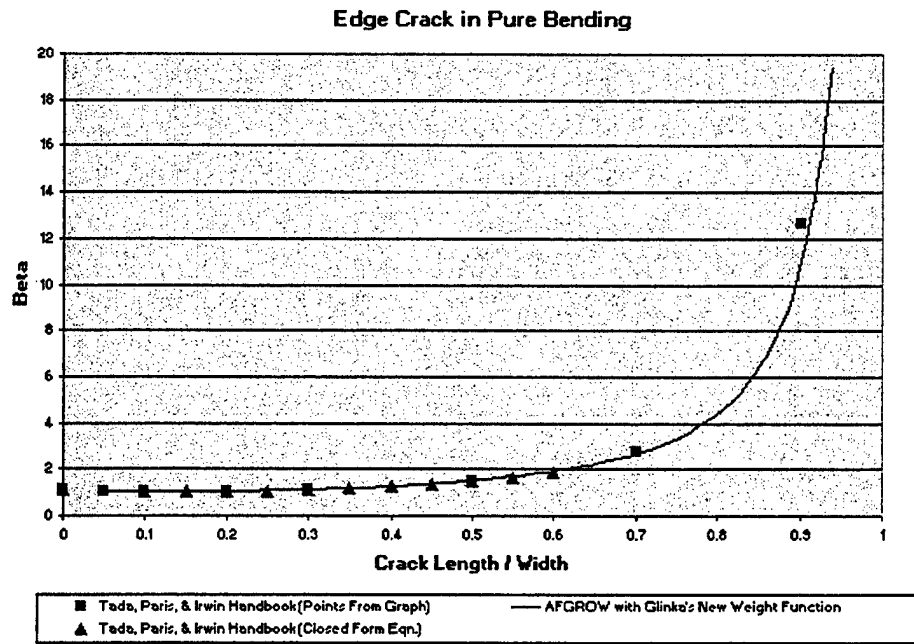


Figure 57: Edge Crack Under an Out-of-Plane Bending Load

The above figures show a comparison between beta values for the weight function case and the corresponding standard stress intensity factor solution. The comparisons show very good agreement to the standard closed-form solutions. There is some divergence at the longer crack lengths. This is expected due to the limits of the weight function solutions. These errors translate to small differences in crack growth life, since the majority of the life is spent at short crack lengths.

3.2.3.4 Model Dimensions

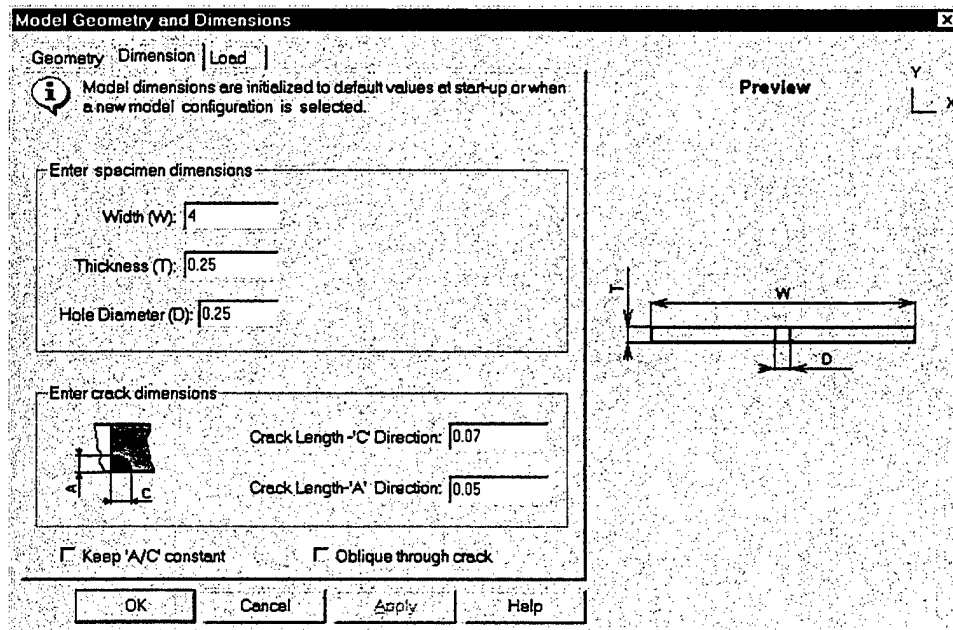


Figure 58: Model Dimensions Dialog

The dimensions dialog is used to set the dimensions of the model and the initial crack size. The options in the dimensions dialog reflect the dimensional features of the selected model. In the case of part-through flaws, the user may choose the option for AFGROW to maintain a constant crack shape ($a/c=\text{constant}$). The preview window will reflect user input dimension changes when the APPLY button is clicked.

3.2.3.4 Model Load

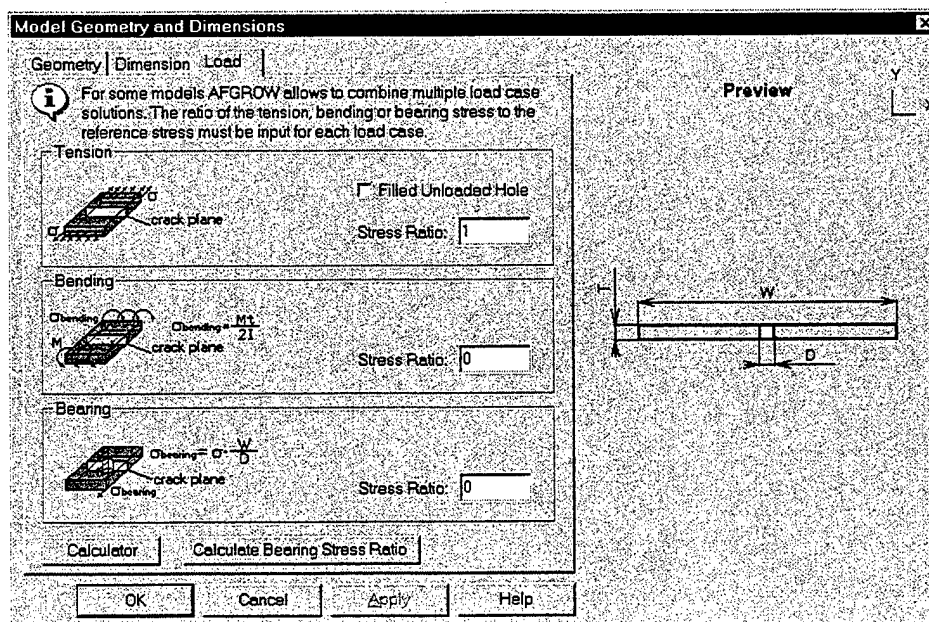


Figure 59: Model Load Dialog

Since some models have multiple load case solutions, AFGROW allows the user to combine these solutions using the superposition method. To use this option, the ratio of the tension, bending, or bearing stress to the reference stress must be input for each load case to be modeled. AFGROW shows the definition of each type of stress in the load tab of the model dialog (see Figure 59). The reference stress is simply the product of the Spectrum Multiplication Factor (SMF) times the current spectrum maximum or minimum value. Since AFGROW uses a single channel spectrum, the inherent assumption is that each load case is in phase and the load case stress to reference stress ratio is constant. Therefore, the ratio may be determined for any applied reference stress. This approach allows a user to perform parametric studies for any number of stress levels by simply changing the value of SMF in the spectrum dialog. It is, however, up to the user to be aware of the definitions of the reference stress and the load case stress to correctly use this capability. Every attempt is made to identify the definition of the load case stresses.

For example:

A 0.25 in. dia. fastener hole in a 0.125 in. thick x 1.0 in. wide plate has a pin load of 200 lbs. The bypass stress is 10 ksi. The bending stress is 5 ksi. If you choose to use the

remotely applied gross stress (bypass stress + bending stress + pin load/(width * thickness)) as the reference stress, then the total gross remote stress is:

$$10 \text{ ksi} + 5 \text{ ksi} + 200/(0.125 * 1.0) * 0.001 = 16.6 \text{ ksi}$$

Therefore,

$$\text{The tensile stress ratio is: } 10/16.6 = 0.6024$$

$$\text{The bending stress ratio is: } 5/16.6 = 0.3012$$

$$\text{The bearing stress ratio is: } (200/(0.25 * 0.125) * 0.001)/16.6 = 0.3855$$

These ratios have nothing to do with a "percent load transfer." There is no limitation that these ratios add to 1.0. Depending on the situation, the ratios can easily be much greater than 1.0. The reason the ratios do not add to 1.0 in this case is because the stress intensity solution for the bearing load case is based on bearing stress instead of gross stress. It is necessary to "fool" AFGROW to use a common reference stress. It is generally a good practice to use gross stress as the reference since the majority of models use gross stress and it will usually minimize any necessary conversions.


A calculator option is available to aid the user in making the appropriate calculations.

Note: For models with tension and bearing load solutions, AFGROW includes an option to calculate the bearing stress ratio automatically based on the tension stress ratio using the following relationship:

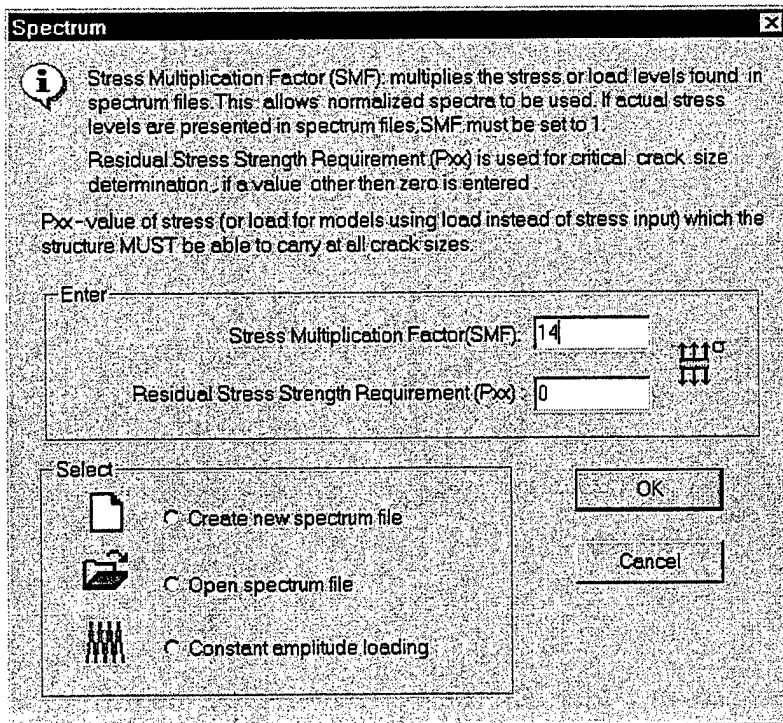
$$\text{Bearing Stress Ratio} = (1 - \text{Tension Stress Ratio}) * W/\text{Dia.}$$

This assumes that the input stress spectrum and spectrum multiplication factor are referenced to the remote tensile gross stress. In addition, this option will not function in cases where a non-zero bending stress ratio is applied. If a bending stress component is included, the user must calculate each stress ratio as shown in the example at the top of this page.


3.2.4 Input Spectrum

Toolbar Icon: 

The spectrum dialog, Figure 60, provides a means of specifying the load/stress spectrum to be used by AFGROW.



Spectrum

 Stress Multiplication Factor (SMF): multiplies the stress or load levels found in spectrum files. This allows normalized spectra to be used. If actual stress levels are presented in spectrum files, SMF must be set to 1.

Residual Stress Strength Requirement (Pxx) is used for critical crack size determination; if a value other than zero is entered.

Pxx - value of stress (or load for models using load instead of stress input) which the structure MUST be able to carry at all crack sizes.

Enter

Stress Multiplication Factor (SMF):

Residual Stress Strength Requirement (Pxx):

Select

☐ Create new spectrum file

☐ Open spectrum file

☐ Constant amplitude loading

OK

Cancel

Figure 60: Input Spectrum Dialog

3.2.4.1 Spectrum Dialog Options

3.2.4.1.1 Spectrum Multiplication Factor (SMF)

The spectrum multiplication factor is multiplied by each maximum and minimum value in the user input stress spectrum. This allows a user to input spectra, which are normalized and simply use one factor to predict the life for different stress levels. Of course, this can be done for non-normalized spectra as well, but may be awkward since it would require the user to calculate the ratio to the actual maximum value in a spectrum.

3.2.4.1.2 Residual Stress Strength Requirement (Pxx)

This value is the source of some confusion, but it is really a simple variable. It is simply the value of stress (or load for models using load instead of stress input), which the structure MUST be able to carry at all crack sizes. This value is NOT multiplied by SMF. It is very useful for cases in which you don't know when the maximum stress (or load) will occur and you wish to check for failure at all times for this condition. If you set this value to zero (default) failure will occur based on the current applied stress (or load). If you have a large spectrum with only one high stress (or load), you could over predict the life depending on what the crack size is when the high load was applied.

3.2.4.1.3 Create New Spectrum File

Opens the Spectrum wizard that guides user through several steps:

Step 1: Spectrum Information

At least two files are required to specify any spectrum for AFGROW. The first file is called a spectrum information file that is named [filename].sp3 and the subsequent file(s) contain the actual spectrum data (see Figure 61). The filename convention is [filenameXX].sub, where XX is a two digit file number (from 01 to 99).

Dialog

The Spectrum Wizard creates SPECTRUM INFORMATION FILE which is required to define the load/stress history for a given crack growth analysis. Spectra may broken into several sub-spectra and sub-spectra may be grouped and divided among a number of sub-spectrum files.

Enter

Base Filename (no extension): C:\PROGRA~1\AFGROW\spectrum

Spectrum Title: Title

Label for Sub-spectrum: Label

Number of files: 1

< Back Next > Cancel Help

Figure 61: Spectrum Information Dialog

The information entered in this dialog will be saved in the [filename].sp3, which this wizard will create.

Wizard Options:

Base Filename: The filename of the spectrum information file without an extension.

Spectrum Title: Provided for reference or documentation purposes.

Label for Sub-spectrum: Provided to identify what each sub-spectrum represents (flights, hours, blocks, etc.).

Number of Files: Number of files containing the actual spectrum data.

Note: While it is acceptable to use a single file for the actual spectrum data, it may be useful to divide the data in more than one file so it is easier to edit the files if necessary.

AFGROW can work with a spectrum file of any size, but no sub-spectrum may exceed 4MB. The number of sub-spectra is unlimited.

Help: Displays the help topic for this step. Users may also press F1 for help.

Cancel: Cancels your previous actions and closes the Wizard.

Back: Disabled in this step.

Next: Move forward to the next step.

Step 2: Type of Spectrum

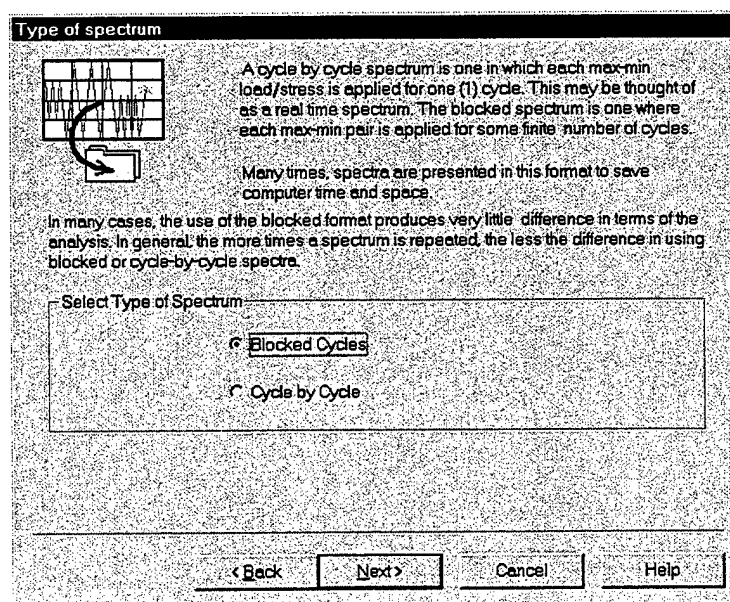


Figure 62: Spectrum Type Dialog

AFGROW uses the term Blocked spectrum, to indicate that each Max, Min Stress level may consist of multiple cycles.

The term Cycle by Cycle means that each Max, Min Stress level may only have one cycle.

Note: Although AFGROW expects a Cycle by Cycle spectrum to have one cycle per level, the format of the data must be in the form Max Min 1, where 1 is the number of cycles. In this way, the file format is consistent. AFGROW will not except a Cycle x Cycle spectrum unless the number of cycles for each stress level is one.

Wizard Options:

Help: Displays the help topic for this step. Users may also press F1 for help.

Cancel: Cancels your previous actions and closes the Wizard.

Back: Move back to the previous step.

Next: Move forward to the next step.

Step 3: Number of Sub-Spectra

Number of Sub-spectra

There are limits, in manual mode, placed on the number of sub-spectra that can make up a spectrum. The limits are 10 sub-spectra per file.

Enter Number of Sub-spectra in file #1

Number of Sub-spectra: 1

☒ Import from file

Browse...

< Back Next > Cancel Help

Figure 63: Sub-Spectra Dialog

Wizard Options:

Number of Sub-spectra: used only for manual spectrum data entry.

Import from File: The wizard can import a complete spectrum file containing an unlimited number of sub-spectra. This file may be a standard AFGROW spectrum file *.sub or a user created ASCII file in the following format:

[number of sub-spectra]

[number of stress levels in a given sub-spectrum]

[max stress] [min stress] [cycles]

.....

[number of stress levels in a given sub-spectrum]

[max stress] [min stress] [cycles]

.....

Browse: Opens Standard Windows Open File dialog if import from file option is selected.

Help: Displays the help topic for this step. Users may also press F1 for help.

Cancel: Cancels your previous actions and closes the Wizard.

Back: Move back to the previous step.

Next: Move forward to the next step.

Step 4: Number of Stress Levels

Sub-spectra are the smallest unit of the total spectrum that AGROW can read into memory at once. They are the building blocks of any AFGROW spectrum. If the total spectrum will fit in the allocated memory (currently 4MB), then all of the data may be placed in a single sub-spectrum. The minimum size of a sub-spectrum is one stress level.

Number of Stress levels

There are limits, in manual mode, placed on the number of stress levels that can make up a spectrum. The limits are 25 levels per spectrum.

File #1 Sub-spectrum #1

Enter Number of stress levels

Number of Stress levels: 11

☐ Import single subspectrum from file

Browse...

< Back Next > Cancel Help

Figure 64: Stress Level Dialog

Wizard Options:

Number of Stress Levels: used only for manual spectrum data entry.

Import single sub-spectrum from file: The wizard can import a file containing the stress levels for a given sub-spectrum. This file must be an ASCII file in the following format:

[number of stress levels in a given sub-spectrum]

[max stress] [min stress] [cycles]

[max stress] [min stress] [cycles]

.....

[max stress] [min stress] [cycles]

Browse: Opens Standard Windows Open File dialog if import from file option is selected.

Help: Displays the help topic for this step. Users may also press F1 for help.

Cancel: Cancels your previous actions and closes the Wizard.

Back: Move back to the previous step.

Next: Move forward to the next step.

Step 5: Stress Levels

This page is only used for manual spectrum data entry. Maximum of 25 stress levels may be entered manually. If larger spectra are required, use the read sub-spectrum from file option.

Set	Max	Min	Cycles
1	1.000000	0.000000	1
2	0.700000	-0.300000	10
3	0.800000	0.100000	50

Figure 65: Stress Levels

Simply highlight the row you wish to edit in the table (click on it), and enter the values in the appropriate box above the table. Pressing [enter] will cause the change to be registered in the table.

Wizard Options:

Help: Displays the help topic for this step. Users may also press F1 for help.

Cancel: Cancels your previous actions and closes the Wizard.

Back: Move back to the previous step.

Next: Move forward to the next step.

Step 6: Finish

This is the final dialog box for the spectrum creation wizard.

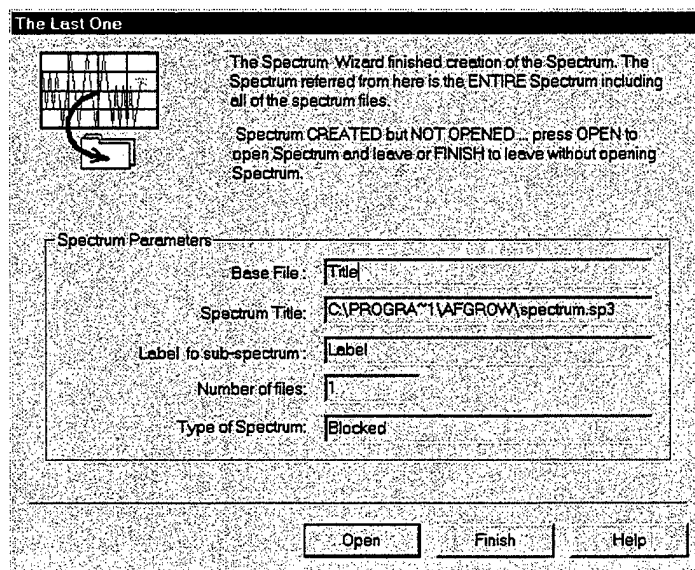


Figure 66: Spectrum Wizard Finish Dialog

The basic spectrum information for the newly created spectrum is shown in this dialog.

Wizard Options:

Open: Saves and Opens the new spectrum in AFGROW and closes the wizard.

Finish: Saves the spectrum file and closes the wizard. Note: The spectrum that was created WILL NOT be opened. The newly created spectrum must be opened before it can be used.

Help: Displays the help topic for this step. You can also press F1 for help.

3.2.4.1.4 Open Spectrum File

Opens the Windows standard Open File Dialog. The Open File Dialog will look in the AFGROW directory by default, but the spectrum files may be located in any directory. The user may select a previously created AFGROW spectrum for use in a given life prediction analysis. **All spectra must be cycle counted** (see section 3.5.4).

3.2.4.1.5 Constant Amplitude Loading

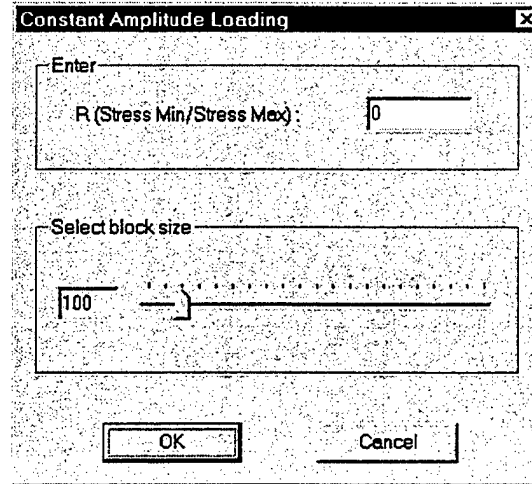


Figure 67: Constant Amplitude Spectrum Dialog

This dialog provides a method to generate a simple constant amplitude loading spectrum. The stress ratio (R) is ratio of the minimum to maximum stress levels³. The block size is used to determine the number of constant amplitude cycles in one pass of the constant amplitude spectrum. AFGROW uses a Vroman integration scheme to help reduce the time required for life analysis. The use of larger blocks will tend to reduce the time required for analysis, but may also reduce the accuracy depending on other user defined software settings.

3.2.4.2 General Spectrum Format Information

At least two files are required to specify any spectrum for AFGROW. The first file is called a spectrum information file (*ASCII text file*) which is of the form [filename].sp3 and is constructed as follows:

[Title]

[sub-spectrum label] (i.e. Flight, Block, Hour, etc.)

³ The maximum value is assigned to be 1.0. The Stress Multiplication Factor (SMF) is required to set the actual maximum stress (or load) value since it is multiplied by each value in a given spectrum.

[*type of spectrum*] (Either BLOCKED or CYCLExCYCLE)

[*number of files to follow*]

The other files associated with the spectrum contain the actual stress (or load) information. Remember that if the spectrum is specified as CYCLExCYCLE, then it MAY NOT have any level (max-min pair) with more than 1 cycle. Also, the spectrum is assumed to have been cycle counted. There are a number of cycle counting programs available in the open literature. AFGROW provides an optional cycle counting tool in the tools menu (see section 3.5.4). In any case, these spectrum data files (*ASCII text*) are named [*filename01.sub*], [*filename02.sub*], ..., etc. These files are constructed as follows:

[*Sub-spectrum Number*] [*number of levels*]


[*max*] [*min*] [*cycles*]

.....

.....

The above pattern is simply repeated for as many sub-spectra as desired. If two files are specified in the [*.sp3*] file, there MUST be a [*filename02.sub*] file⁴. The maximum and minimum values are floating point values and the cycles are integer values. A text editor or a simple program may be used to generate these files.

3.2.5 Input Retardation

Toolbar Icon: 

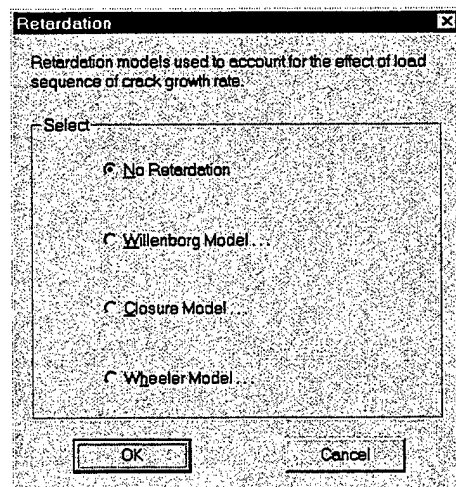


Figure 68: Retardation Model Dialog

There are currently four choices of load interaction, or retardation models in AFGROW. The models can be accessed through either the standard menu dialog or by using the pull-down menu located on the toolbar.

⁴ ALL files associated with a spectrum have the same root name [*filename*].

Note: Each model has a user adjustable parameter that is used to tune the model to fit actual test data. Ideally, a parameter should be a material constant, which is independent of other variables such as spectrum sequence or load level. Some models seem to work better than others in this regard, but there is a need to reproduce results for various types of retardation models. These models are provided to be used at the users discretion and responsibility.

The details of the No Retardation, Generalized Willenborg, Closure, and Wheeler models are given in the following sections.

3.2.5.1 No Retardation

This is the default option in AFGROW. When this option is selected, no spectrum load interaction effects will be assumed.

3.2.5.2 Generalized Willenborg Model

The Generalized Willenborg model [43] is one of the most common load interaction models used in crack growth life prediction programs. The model is based on early fracture mechanics work performed at Wright-Patterson AFB, OH and was named after a student who worked on the model. The model uses an "effective" stress intensity factor based on the size of the yield zone in front of the crack tip. The formulation of the Willenborg retardation model used in AFGROW is given below:

$$K_{max}(eff) = K_{max} - K_{red}$$

$$K_{min}(eff) = K_{min} - K_{red}$$

$$R(eff) = K_{min}(eff)/K_{max}(eff)$$

$$K_{red} = \phi \left(K_{max}(ol) \sqrt{1 - \frac{(x - x(ol))}{Ry(ol)}} - K_{max} \right)$$

$$\phi = (1 - \Delta K_{Threshold}/K_{max})/(SOR - 1)$$

$$Ry(ol) = \left(\frac{K_{max}(ol)}{Yield} \right)^2 \left(\frac{1}{PSX \pi} \right)$$

Where:

x : Crack Length

x(ol) : Crack Length at Overload

$\Delta K_{\text{Threshold}}$: Threshold value of DK at $R = 0$

Yield : Material yield strength

PSX : Stress State in a Given Crack Growth Direction (2.0 (Plane Stress) - 6.0 (Plane Strain))

The subscript (ol) refers to an overload condition. It is changed each time that an applied maximum stress (or load) exceeds a previous maximum, or when the current yield zone size (R_y) grows beyond the yield zone created by an overload ($R_y(ol)$). The value, ϕ , is simply a parameter used in the Generalized Willenborg model. The $\Delta K_{\text{Threshold}}$ is the lowest value of ΔK that will cause a crack to grow for $R = 0$. The value is based on user input for the crack growth rate model being used in a given prediction.

Retardation Parameter:

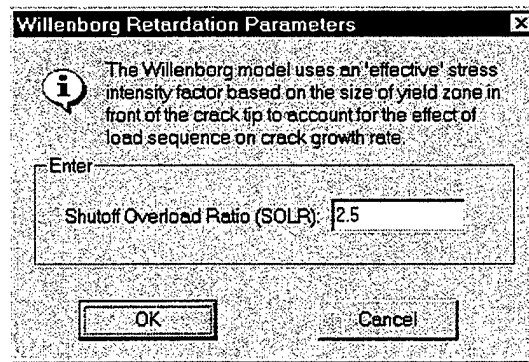


Figure 69: Willenborg Retardation Parameter Dialog

SOR : Shut-off Ratio - Ratio of overload maximum stress to the subsequent maximum stress required to arrest crack growth

The exact value of the SOR is varied to adjust the life prediction to match test results. Ideally, the SOR should be a material parameter, which is insensitive to spectrum or stress level. However, this does not always work out. The following is a list of common SOR values for some materials:

Aluminum: SOR = 3.0

Titanium: SOR = 2.7

Steel: SOR = 2.0

Many crack growth programs use the Chang acceleration model [44] with the Willenborg retardation model to account for the effect of compressive stress (or load) cycles. The Chang model requires the use of negative stress intensity values. AFGROW does not consider negative stress intensity factors to be valid (in general). In place of the Chang

acceleration model, AFGROW uses the following method to account for the effect of compressive stresses (or loads):

$$Ry(ol) = \left(1 - 0.9 ABS \left(\frac{\sigma_{compression}}{\sigma_{overload}} \right) \right) Ry(ol)$$

Using the absolute value of the ratio of the compressive stress (or load) to the overload stress (or load) reduces the size of the current overload yield zone. This method will NOT increase the effective stress intensity; it will merely reduce the retarding effect of a previous overload. Therefore, the Willenborg model used in AFGROW can NEVER result in a life prediction that is less than the life prediction with no retardation.

3.2.5.3 Closure Model

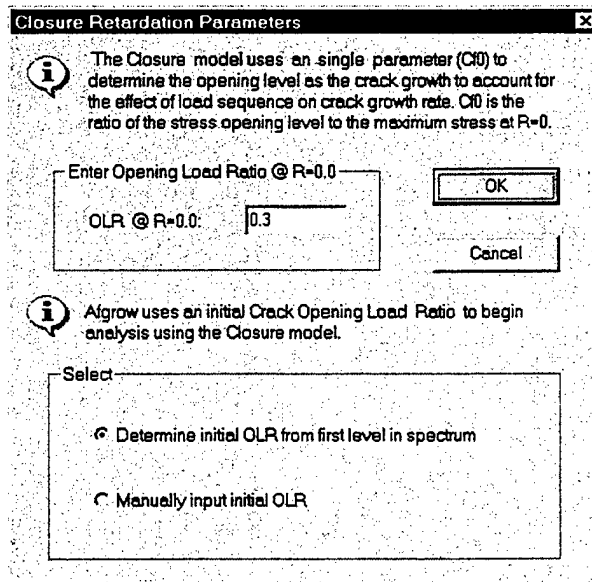


Figure 70: Closure Retardation Model Dialog

The closure model in AFGROW is a fairly simple single-parameter plasticity model. The model is based on early fracture mechanics work by Erdogan and Elber and more recent models proposed by Dr. Matthew Creager and Dr. Sunder [2-4]. The model, developed by Mr. James Harter, basically expanded a constant closure model originally developed by Dr. Creager while he and Mr. Harter were involved in performing damage tolerance analyses for the B-2 Bomber in 1982-83.

It is important to understand that this model is called a closure model because it is based on the idea that the crack is “closed” when no load is applied and a certain load must be applied to “open” the crack tip. Some researchers believe that yielded material in the wake of a growing crack acts as a wedge behind the crack tip [45]. This yielded material is forced to be in compression by the elastic material surrounding it. Other researchers believe that this plastic wake is merely a surface phenomenon caused by the difference between the plane stress state at the surface and an internal plane strain state. They believe that the apparent contact behind the crack tip is merely the result of natural stress

equilibrium and plays a very minor role in crack growth behavior [46, 47]. The later researchers believe that there is only a significant compressive residual stress in FRONT of the crack tip. This compressive residual stress must be overcome by applied tensile loading before the crack can extend.

In either case, there is some minimal applied tensile load that must be reached before the crack may extend. In AFGROW, this value is referred to as the "opening" load. The early closure work by Elber, et al., [2-4] showed a relationship between the maximum applied stress and this opening stress. The closure factor, C_f , was defined as the ratio of the opening stress to the maximum applied stress and was demonstrated to be a function of stress ratio (R).

Here's how the AFGROW closure model works:

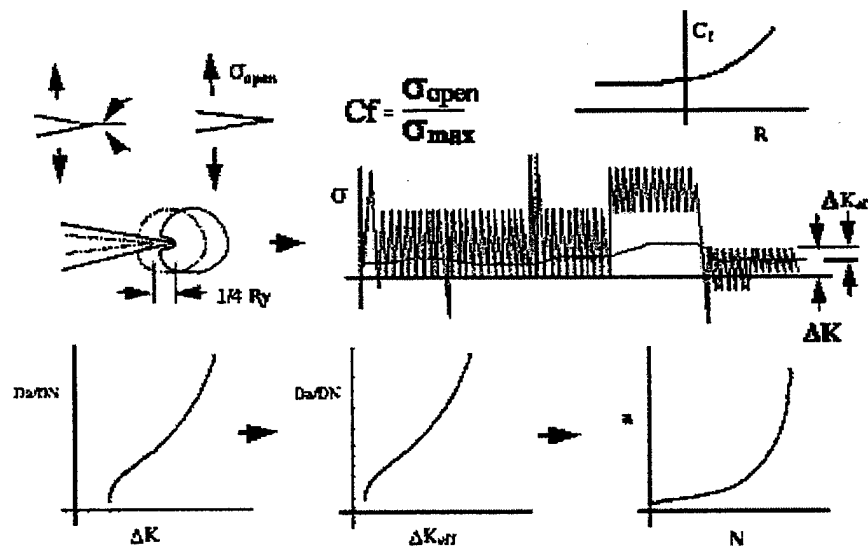


Figure 71: AFGROW Closure Model

The user must input a value for the crack opening load ratio for $R=0.0$ (C_{f0} – the single closure parameter). AFGROW uses the following relationship for C_f :

$$C_f = 1.0 - [(1.0 - C_{f0})(1.0 + 0.6R)(1.0 - R)]$$

$$C_f = R, \text{ for } R > R_{hi}$$

$$R = R_{lo}, \text{ for } R < R_{lo}$$

Note: Since the function for C_f reaches a minimum at $R = -0.333$, AFGROW ensures that the stress ratio used to determine C_f will not be less than -0.333 . This ONLY affects the C_f calculation to prevent the opening level from increasing as R decreases. R_{hi} and R_{lo} are defined in section 3.2.2.

The initial crack opening level can either be determined from the first cycle of the input spectrum OR may be input by the user in case any previous load history is known.

According to work by Dr. Sunder, the C_f value expected for a given stress ratio will not be reached until the crack grows 1/4 of the way through the yield zone created by the maximum stress. The opening level is varied linearly from the current value within the 1/4 yield zone distance. AFGROW keeps track of the current overload cycle by defining an overload condition whenever (crack length + yield zone) > previous overload - as is the case in the Willenborg model.

Compressive loads/stresses are treated a bit differently in that the opening level may be INSTANTANEOUSLY shifted to the level determined by the equation above for an R value equal to the ratio of the compressive minimum load/stress to the current maximum overload load/stress. The INSTANT change in opening level is made IF the maximum value for a given cycle IS an overload (yield zone extends beyond previous overload case) AND the opening level is LOWER than the current opening level OR the maximum value for a given cycle IS NOT an overload AND the opening level (based on the R value determined from the compressive value and the current overload) is LOWER than the current opening level. The idea is that while a crack must grow into the plastic wake of tensile overloads to fully develop a given opening level, a compressive cycle can instantly cause the residual stress field to be changed. If any given compressive load/stress is not low enough to cause the opening level to fall below the current value, then there is no reason to change the opening stress.

When an overload cycle contains a compressive minimum, the overload yield zone size is reduced by 10 percent of the absolute value of the stress ratio for that cycle. This reduction is made to help account for the effect of the compressive minimum. This reduces the effect of the overload since it will take fewer subsequent cycles to grow through a smaller overload yield zone. The quantity, 10 percent, was determined based on actual test data for common aircraft alloys tested in-house at Wright-Patterson AFB and some very helpful data provided by Mr. Kevin Walker [48].

Finally, an effective ΔK is determined from the difference between the maximum K and the K value for the opening load/stress level. Since the input crack growth rate data is NOT based on the effective ΔK , a conversion back to apparent ΔK is made in the crack growth rate module. This conversion, however, is based on the C_f value for the current load cycle.

$$\Delta K_{\text{apparent}} = \Delta K_{\text{eff}} \frac{(1-R)}{(1-C_f)} ; \text{ for } R \geq 0.0$$

$$\Delta K_{\text{apparent}} = \frac{\Delta K_{\text{eff}}}{(1-C_f)} ; \text{ for } R < 0.0^5$$

⁵ This relationship is used here because AFGROW uses K_{max} , not ΔK , when $R < 0.0$

In this way, the result of predictions made using constant amplitude spectra will give the same results as the no retardation case. There may be a slight difference in the closure model vs. no retardation for constant amplitude blocked spectra. This is due to the fact that individual blocks are divided into smaller blocks in the closure model to ensure that a given crack will NOT grow beyond 1 percent of the current overload yield zone. This may be verified by use of a single cycle constant-amplitude spectrum. The results for the closure model will match those of the no retardation model for this case - of course; there will be an increase in runtime.

3.2.5.4 Wheeler Model

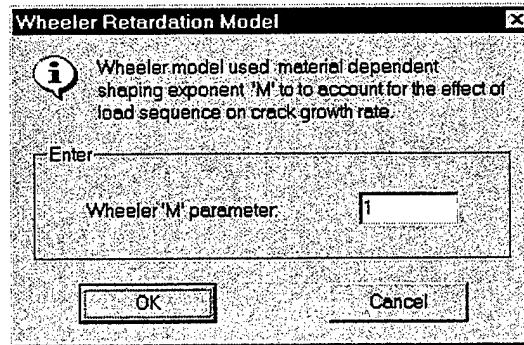


Figure 72: Wheeler Model Dialog

The Wheeler retardation model [49] is one of the most empirical load interaction models in use in Fracture Mechanics today. It works by modifying the current crack growth rate with a "knock-down" factor based on the ratio of the current yield zone size to the difference between the effective crack length of an overload condition and the current crack length. Here's how it works:

$$\frac{da}{dN} = C_p \left(\frac{da}{dN} \right)$$

Where:

$$C_p = \left(\frac{R_y}{X_{eff(ol)} - X} \right)^m$$

X is the crack length

X_{eff} is the crack length plus the yield zone size

$$R_y = \left(\frac{K_{max}}{Yield} \right)^2 \left(\frac{1}{\pi PSX} \right)$$

Note: AFGROW uses the Irwin yield zone equation (and the current stress state) to determine the yield zone size. The subscript (ol) refers to an overload condition. It is changed each time that an applied maximum stress (or load) exceeds a previous maximum, or when the current yield zone size (R_y) grows beyond the yield zone created by an overload ($R_y(ol)$). PSX is the stress state for the given crack length (2 – Plane Stress, 6 – Plane Strain).

Retardation Parameter:

m : Wheeler exponent

The value of the Wheeler exponent, m , is determined from test data for a given material, spectrum, stress level, etc. As mentioned above, this model is extremely empirical and the m value, which gives good correlation to test data, has been known to be dependent on MANY test parameters. Users should use this model with caution.

3.2.6 Input Stress State

Toolbar Icon:

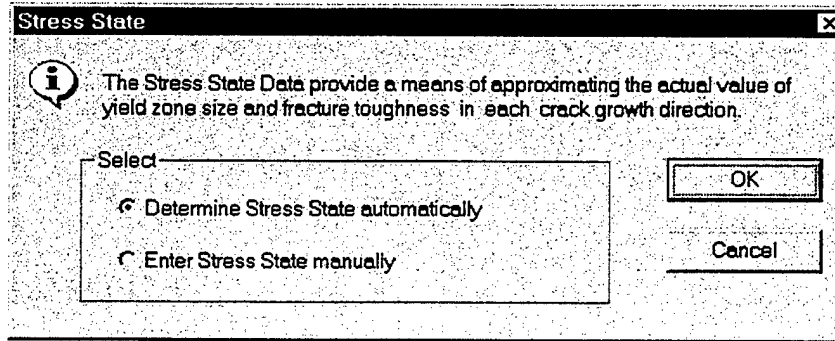


Figure 73: Stress State Dialog

There are currently two choices in AFGROW for Stress State: Automatic Stress State Determination and User Specified. AFGROW uses a stress state index of real numbers that range from 2 to 6. The range was chosen because of the relationship between stress state and the Irwin yield zone size.

$$\text{Plane Stress: Yield Zone Size} = \left(\frac{K_{\max}}{Yield} \right)^2 \frac{1}{2\pi}$$

$$\text{Plane Strain: Yield Zone Size} = \left(\frac{K_{\max}}{Yield} \right)^2 \frac{1}{6\pi}$$

AFGROW uses the stress state index to determine the yield zone size, which is required for the load interaction models, AND to determine the appropriate value of fracture toughness. The yield zone size is determined as follows:

$$\text{Yield Zone Size} = \left(\frac{K_{\max}}{\text{Yield}} \right)^2 \frac{1}{(\text{index})\pi}$$

The actual value of fracture toughness that defines the stress intensity failure limit for a given geometry is often called the apparent fracture toughness since it is determined by the given geometry and applied failure stress. The highest possible value of fracture toughness is the plane stress fracture toughness and the lowest possible value is the plane strain fracture toughness. The plane stress and strain fracture toughness values are material properties. The apparent fracture toughness value is determined by a linear interpolation between the plane strain (K_{IC}) and plane stress (K_C) fracture toughness values input by the user.

$$\text{Apparent Fracture Toughness} = K_{IC} + \frac{(6.0 - \text{index})}{4.0} (K_C - K_{IC})$$

The stress state index is a function of the specimen thickness and maximum applied stress intensity. Specimens that are relatively thin are generally operate under plane stress conditions (index = 2.0) and thick specimens are generally plane strain (index = 6.0).

3.2.6.1 Automatic Stress State Determination

The default choice for stress state determination in AFGROW is to automatically determine the stress state index based on K_{\max} and specimen thickness for each applied load/stress cycle. The relationship between K_{\max} , thickness (t), and stress state index [50] is:

$$\text{Index} = 6.7037 - \frac{1.4972}{t} \left(\frac{K_{\max}}{\text{Yield}} \right)^2$$

If Index > 6.0, Index = 6.0 (Plane Strain)

If Index < 2.0, Index = 2.0 (Plane Stress)

The above relationship has been verified with fracture test data for several metal alloys. The complete details will be published at a later date. The test results are shown in Figure 74.

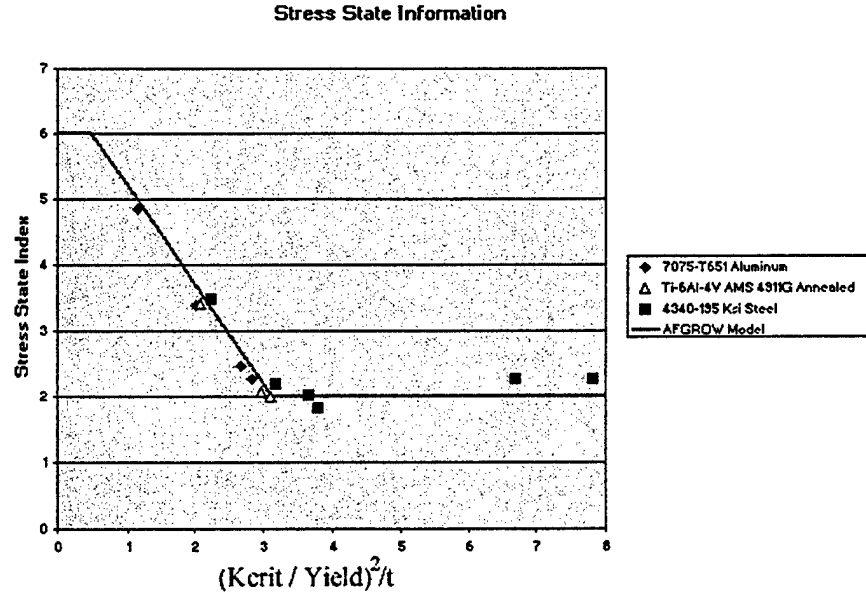


Figure 74: Stress State Information

According to David Broek [51], the plane strain condition is:

$$\text{Plane Strain (index} = 6.0) : \left(\frac{K_{crit}}{Yield} \right)^2 \leq 0.47t$$

The ASTM standard for a plane strain condition [52] is:

$$t \geq 2.5 \left(\frac{K_{crit}}{Yield} \right)^2$$

The ASTM standard is slightly more conservative, but it meets Dr Broek's plane strain condition.

There is no definitive reference for the plane stress condition. The test data shown in Figure 74 for three common aircraft alloys (aluminum, titanium, and steel) led Mr. Harter [50] to believe that the following plane stress condition may be applied for these alloys:

$$\text{Plane Stress (index}=2.0) : \left(\frac{K_{crit}}{Yield} \right)^2 \geq \pi t$$


A linear equation was used to determine intermediate stress state indices for conditions between the plane stress and strain limits. Plane stress and strain fracture toughness values were known for the alloys used in the test program. Each center cracked (MT) specimen was pre-cracked to various crack lengths and loaded monotonically to failure. The failure stress and crack length was used to determine the critical stress intensity

factor. The stress state index was determined by linear interpolation based on the plane stress and strain fracture toughness values for each material.

3.2.6.2 User Specified Stress State

Users have an option to input stress state index values. If this option is selected, AFGROW will use a constant value for stress state index in a given crack growth dimension. The index range is a real number from 2 to 6, where 2 is used for Plane Stress and 6 for Plane Strain. The user-specified value(s) will remain constant during the life prediction calculations and will be used to determine the apparent fracture toughness.

3.2.7 Input User-Defined Beta

Toolbar Icon: 

Users can input their own solutions through the user-defined beta option. However, to use this option, the user must first select either the 1-D or 2-D user defined geometry from the Standard Solutions dialog (see section 3.2.3). Beta factors are defined as follows:

$$\beta = \frac{K}{\sigma \sqrt{\pi x}} ; \text{Where } x \text{ is the appropriate crack length}$$

The crack length dimension in the thickness direction is the a-dimension and the crack length in the width direction is the c-dimension. Application and user defined solutions are identified in the beta solution column in the geometry tab of the model dialog (see Figure 47, Section 3.2.3). There are only two user-defined models among the standard solutions since AFGROW only handles 1-D or 2-D cracks. These geometries are simply generic models, which depict either a 2-D crack (2 crack dimensions) or a 1-D crack (1 crack dimension). Since the user inputs the beta values, the actual geometry is taken into account by the beta values themselves. The image in the animation frame is merely showing a generic view since it is difficult to show all possible user-defined geometries.

3.2.7.1 One-Dimensional User Defined Betas



The one-dimensional user-defined beta option is used when a user has an existing stress intensity factor solution (in the form of a beta table) for any crack that may be described with one length dimension (1-D) to input in AFGROW.

The geometric beta values are NOT calculated by AFGROW, but are merely interpolated from a one-dimensional user defined table of beta values. Users must supply beta values at various crack lengths so that the appropriate value at a given crack length may be interpolated. This model is shown as an edge cracked plate in the animation frame. The representation of the model is merely meant to indicate the one-dimensional nature of the crack. It was not possible to create representations of all possible geometries that may be modeled using user defined beta factors.

For the [c] crack length dimension: $K = \sigma \sqrt{\pi c} \beta(c)$

When the user-defined beta option is selected for a through crack case, the dialog box shown in Figure 75 appears:

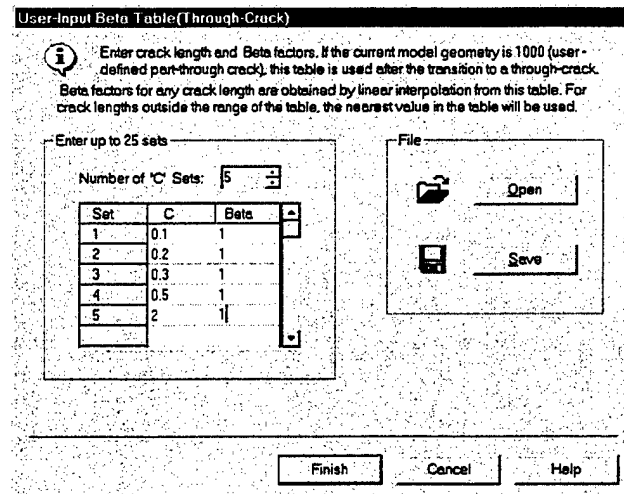


Figure 75: Through Crack User-Defined Beta Table Dialog

The initial crack length should be the same as the initial part through crack length in the C direction, which will become the through crack. This is because it may be difficult to know what that dimension will be by the time the crack transitions and it is important that the input data cover the entire range of possibilities. AFGROW will NOT extrapolate user-defined betas and will simply use the nearest data in the event the data are out of range.

If the user-defined through crack input data are saved, AFGROW will give it a .bet extension which will be visible the next time this dialog is opened (clicking on the read button will open it again). Just remember which directory the data are in if you decide to save to some directory other than the default.

3.2.7.2 Two-Dimensional User Defined Betas



This option is used when a user has an existing stress intensity factor solution (in the form of a beta table) for any crack which may be described with two length dimensions (2-D) to input in AFGROW.

The geometric beta values are NOT calculated by AFGROW, but are merely interpolated from a two-dimensional user defined table of beta values. Users must supply beta values at various crack lengths so that the appropriate value at a given crack length may be interpolated. This model is shown as a corner cracked plate in the animation frame. The representation of the model is merely meant to indicate the two dimensional nature of the crack. It was not possible to create representations of all possible geometries that may be modeled using user defined beta factors.

For the [a] crack length dimension: $K = \sigma \sqrt{\pi a} \beta(a)$

For the [c] crack length dimension: $K = \sigma \sqrt{\pi c} \beta(c)$

When the beta icon (or User-Defined Beta menu option) is selected, the dialog shown in Figure 76 will appear:

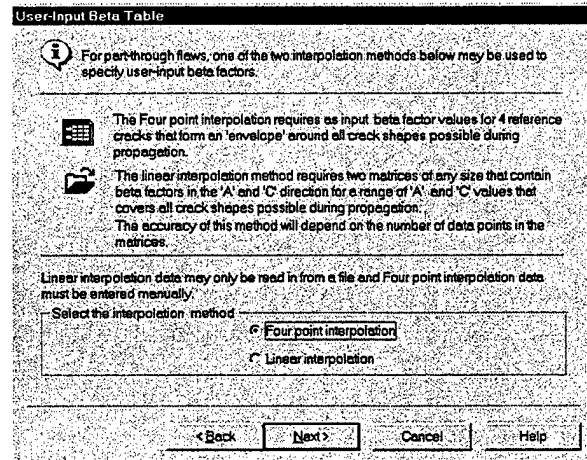


Figure 76: 2-D User Input Beta Dialog

Since beta values for a 2-D crack are dependent on crack shape (a/c), a matrix of beta values are required to determine the appropriate stress intensity factors for each dimension (assuming the dimensions are independent). The two dimensions of crack growth are allowed to grow based on the stress intensity for each dimension. It is not possible to anticipate the changes in crack shape that are possible as the 2-D crack grows under any arbitrary loading.

There are currently two choices in AFGROW to input User Defined Betas for Part-Through Cracks: Four Point and Linear. Actually both use linear interpolation. The Four Point method attempts to provide a simpler method of interpolation, which is based on Schijve's weighted interpolation [53] (without weights, which are model specific). The Linear method is a straightforward double table look-up that must be read from a file.

3.2.7.2.1 Four-Point User-Defined Beta Values

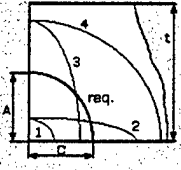
AFGROW will produce the following dialog with crack length suggestions (which may be changed as desired - within the guidelines noted) if the four-point method is selected (see Figure 77).

Four point interpolation

i Enter Beta values for four reference cracks that encompass the expected range of crack growth. Cracks no. 1 and 2 must have an equal 'A' value that is less than or equal to the initial crack depth, 'A'.
Cracks no. 3 and 4 must have an equal 'A' value that is greater than or equal to 95% of the thickness.

Also, cracks no. 1 and 3 must have 'C' values less than or equal to the initial crack length, 'C', and cracks no. 2 and 4 must have 'C' values greater than or equal to the maximum crack length, expected before transition to a through-crack.

During fatigue life calculations, if the current crack falls outside this envelope, it will be assigned Beta values equal to those of the nearest reference crack.



no.	'A'	'C'	Beta 'A'	Beta 'C'
1	0.05	0.07	1	1
2		0.475	1	1
3	0.2375	0.07	1	1
4		0.475	1	1

< Back Next > Cancel Help

Figure 77: Four-Point Beta Interpolation Dialog

This method is offered to allow users to input part through crack beta information for a minimum number of crack lengths. This method is not expected to be terribly accurate, but may be sufficient for cases where there is limited time or resources available for detailed analyses. AFGROW will suggest crack lengths expected to cover the range of lengths in both crack growth directions. The user may also change these values. In either case, beta values for any arbitrary crack shape (a/c) will be determined by linear interpolation on these data. Data will NOT be extrapolated – the nearest point in either direction will be used. It is important for users to know this and enter data that covers the expected range of crack lengths in both directions.

The crack lengths for the c-direction are repeated for each a-dimension (see the dialog box above). It is important to maintain this for the purpose of interpolation.

If the option to keep a/c constant is selected in the model dimensions dialog (Figure 58), all of the crack growth calculations are based on the c-direction. The beta values for the a-direction will not be used in this case. However, the beta values for the a-direction must be filled nonetheless (with 1's if desired). Also, if the betas for the c-direction are not considered to be a function of the a-direction, the data for the c-direction may be simply repeated for the second a-direction (see the dialog box above).

3.2.7.2.2 Linearly Interpolated User-Defined Beta Values

When the linear option is selected, AFGROW will open the standard file open dialog, Figure 78, and will show any files of this type exist in a given directory.

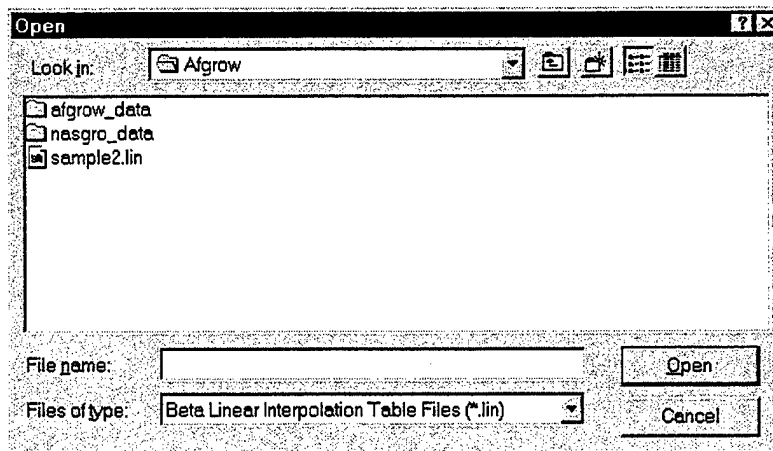


Figure 78: Linear Interpolation Dialog

This information **MUST** be read from a file since it will probably be a relatively large amount of data. The file format is set up in a table format that will make it easy to export from a spreadsheet. In addition, it should be noted that there are **TWO** tables, the first is for the betas in the A-dimension and the second is for the betas in the C-dimension. These data are required to allow AFGROW to interpolate in both crack growth dimensions to find the appropriate beta values (for both dimensions). Also, remember:

- The matrices must be square and both must be the same size.
- The crack lengths for which the Beta values are specified must be the same for each table. The A and C lengths do not have to be the same, just the C's and the A's must match in both tables.
- More data provides more accuracy.

The matrices are square because it is easier to work with square matrices. In addition, the interpolation accuracy is generally better if there are an equal number of crack lengths in both directions. This arrangement handles the most general case, where the crack shape is not known in advance and is allowed to change based on the local growth rate. It may seem excessive in cases where a user may want to keep the crack shape (a/c) constant, but it is easy to copy columns or rows of data in a spreadsheet. If the option to keep a/c constant is selected, all of the crack growth calculations are based on the c-direction. The beta values for the a-direction will not be used in this case. However, the table for the a-direction must be filled nonetheless (with 1s if desired). Also, if the betas for the c-direction are not considered to be a function of the a-direction, the data for each column may be copied to fill the table for all the a-dimensions.

The second point above merely states that the dimensions used for each matrix (for the a-direction and the c-direction) must match. It should make sense that the dimensions for both tables are the same. Any redundancy is just for the purpose of readability. Again, the lengths used for each dimension do not have to be the same, but the c-lengths used for the a-direction table must match the c-lengths used for the c-direction table. The same goes for the a-lengths for both tables.

The final point mentions accuracy. This is obvious, but more data will yield better accuracy. This is the reason for this option. Users are in control over the amount of data used in this method. AFGROW will merely linearly interpolate in both crack growth directions to determine the beta value used in the life prediction. Data will NOT be extrapolated – the nearest point in either direction will be used. It is important for users to know this and enter data that covers the expected range of crack lengths in both directions. The final line in the file is reserved to let AFGROW know the desired units for the input crack lengths. The enumerated values are 0 for English and 1 for Metric units (see section 4.0 for more information about units). The word (units) should be capitalized in the file.

The [filename].lin file format is as follows ([Blank Spaces] allow the columns to align):

```
[Matrix Order (N)] (Maximum is currently 100)

[Blank Spaces] [ 1st A Length ] [ 2nd A Length ] ... [ Nth A Length ]

[1st C Length] [Beta in A dir.] [Beta in A dir.] .... [Beta in A dir.]

[2nd C Length] [Beta in A dir.] [Beta in A dir.] .... [Beta in A dir.]

.....<data pattern is continued>.....

[Nth C Length] [Beta in A dir.] [Beta in A dir.] .... [Beta in A dir.]

[Blank Spaces] [ 1st A Length ] [ 2nd A Length ] ... [ Nth A Length ]

[1st C Length] [Beta in C dir.] [Beta in C dir.] .... [Beta in C dir.]

[2nd C Length] [Beta in C dir.] [Beta in C dir.] .... [Beta in C dir.]

.....<data pattern is continued>.....

[Nth C Length] [Beta in C dir.] [Beta in C dir.] .... [Beta in C dir.]
[UNITS=0]
```

3.2.8 Input Environment

Toolbar Icon:



Currently, AFGROW allows cyclic environmental effects to be determined based on crack growth rate data obtained for the environment of interest. In the case of some environmental effects (i.e. corrosion (material loss)), the effect may be merely limited to local increased stress levels. However, some environmental effects can have a direct effect on the crack growth rate behavior of a given material. In the later case, the cyclic environmental effect model may be used to more accurately predict crack growth life. AFGROW allows as many as six separate applications of the same or different environments as indicated in Figure 79.

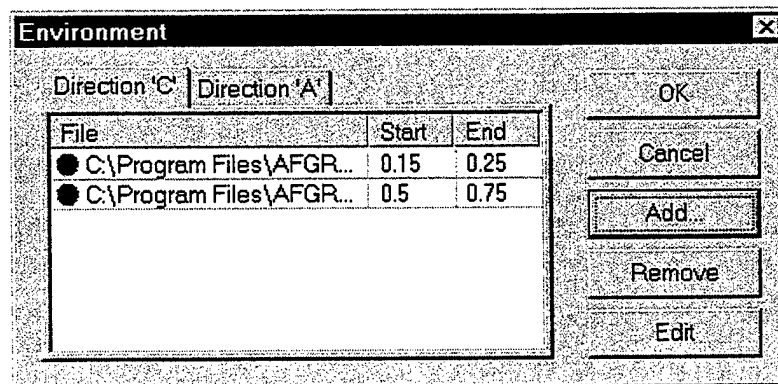


Figure 79: Environment Dialog

For the example above, the depiction of the applied environments is indicated on the model as shown in Figure 80.



Figure 80: Environmental Depiction in the Animation Frame

Each application of a given environment is shown (color-coded) on the specimen in the animation frame. For now, the environmental capability is only available when the "Harter T-Method" (section 3.2.2.4) for crack growth rate data representation is used. The reason for this is because separate crack growth rate data files must be created for the environmental data. The tabular data format was considered to be the most accurate means of representing actual crack growth rate data. The initial capability was designed prior to the development of the tabular look-up crack growth rate model (section 3.2.2.5). The material title used for each material in the material data file in the "Harter T-Method" is compared to the title lines in the environment data file to ensure that data for the same material are being used.

When a user selects the “Add” button in the environmental dialog (Figure 79), the dialog shown in Figure 81 appears.

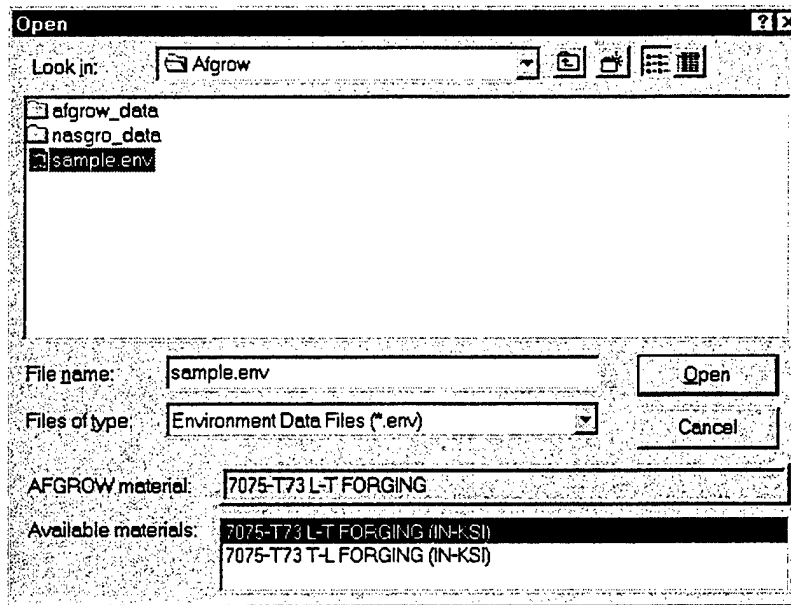


Figure 81: Environmental File Open Dialog

The current baseline material is displayed in the lower portion of the dialog box. Once a file containing the desired environmental crack growth rate data is selected (single left-click), the dialog box displays the titles for the material data available in that file. The environmental data files are simply text files containing much of the same information that is contained in the material files used with the “Harter T-Method” (section 3.2.2.4). There are a few additional parameters that control the transition from the baseline data to the environmental data. The default file extension is [.env].

The format of the file is:

[*Material Title*] (Must match the baseline material title)

[*da/dN*] [*Delta K @R=0*] [*m*] (25 lines of this data – EXACTLY 25 lines)

[*Dist*] [*A1*] [*A2*] [*A3*]

[*Rlo*] [*Rhi*] [*KIC*] [*Yield*]

[*END*] (after the last material)

Refer to section 3.2.2.4 (Harter T-Method) for more information on the variables listed above. Note, that the additional variables: Dist, A1, A2, and A3 are required to characterize the transition behavior as described in the next section.

3.2.8.1 Modeling Environmental Crack Growth Rate Transition Behavior

AFGROW uses a third order polynomial function to interpolate the appropriate crack growth rate as a crack grows through a transition region between two different environments. This is illustrated in Figure 82.

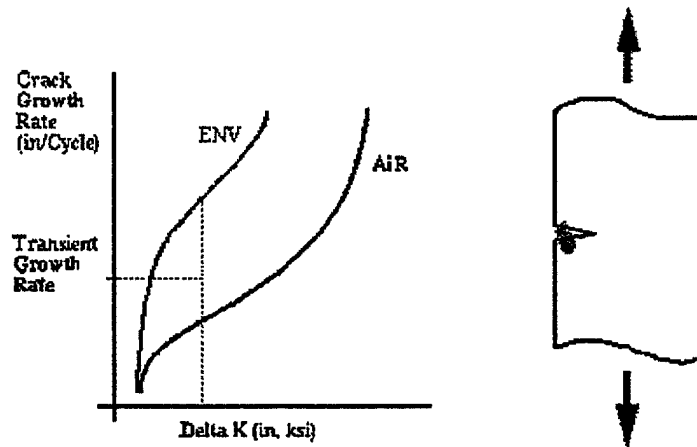


Figure 82: AFGROW Environmental Rate Transition Model

The form of the transition relationship that has been implemented in the current version of AFGROW is as follows:

$$\text{Rate} = \text{Rate1} + \text{Factor} (\text{Rate2} - \text{Rate1})$$

Where:

$$\text{Factor} = A1 (\text{Trans}) + A2 (\text{Trans})^2 + A3 (\text{Trans})^3$$

$$\text{Trans: Fraction of Transition Distance Penetrated (0 - 1)} = \frac{x}{\text{Dist}}$$

x: Relative crack tip position (0 - Dist)

Dist: Maximum distance from environment boundary where crack growth rate is affected

Rate1: Rate curve from which the crack tip is growing

Rate2: Rate curve to which the crack tip is growing

$$A1 + A2 + A3 = 1.0^6$$

⁶ This is due to the boundary conditions: when Trans=1.0, Rate must be equal to Rate2, which means that Factor must also be equal to 1.0

3.2.9 Input Beta Correction

AFGROW includes an ability to estimate stress intensity factors for cases, which may not be an EXACT match for one of the stress intensity solutions in the AFGROW library (section 3.2.3). For example, a case is being modeled with a high stress gradient. It is unlikely that an exact solution would be available, and the creation of a boundary or finite element model would be time consuming. AFGROW offers a method to approximate the solution using a beta correction technique (see Figure 83).

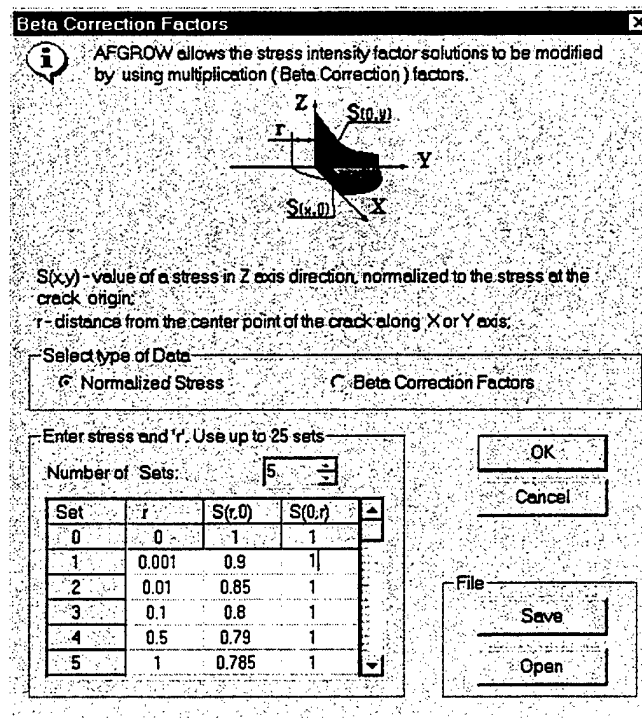


Figure 83: Beta Correction Factor Dialog

Users have the option of entering normalized stress values in the crack plane and allow AFGROW to calculate beta correction factors or enter pre-determined beta correction values.

3.2.9.1 Determine Beta Correction Factors Using Normalized Stresses

AFGROW employs a Gaussian integration method, which uses a point load stress intensity solution from the Tada, Paris, and Irwin Stress Intensity Handbook [54] to integrate a given 2-D unflawed stress field (in the crack plane) to estimate stress intensity values at user defined crack length increments.

Users should choose the standard model with a stress field that is as close as possible to the stress field of interest. Then determine the ratio of the unflawed stress field of interest to the unflawed stress field for the chosen geometry at various crack length intervals. A maximum of 25 points may be input to describe the stress distribution. The intervals should be selected such that linear interpolation would provide a reasonable curve fit

between the points. These intervals do NOT have to be uniform, but there should not be a large change in the slope between adjacent intervals. AFGROW uses a Newton interpolation scheme to determine the Gaussian integration points. If the slope change between intervals is large, the code can generate erroneous integration points. AFGROW will provide a warning message if a large slope change is detected.

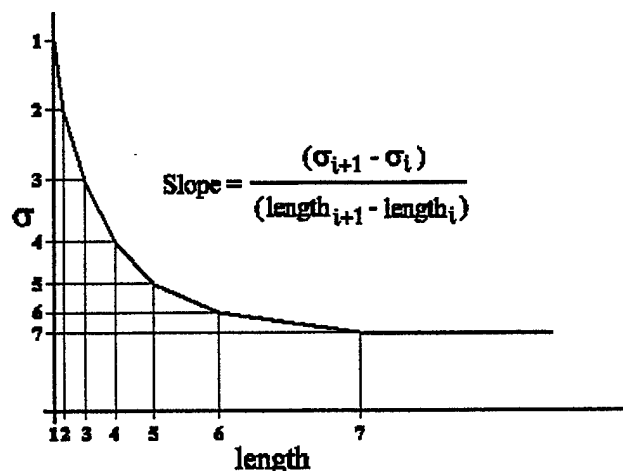
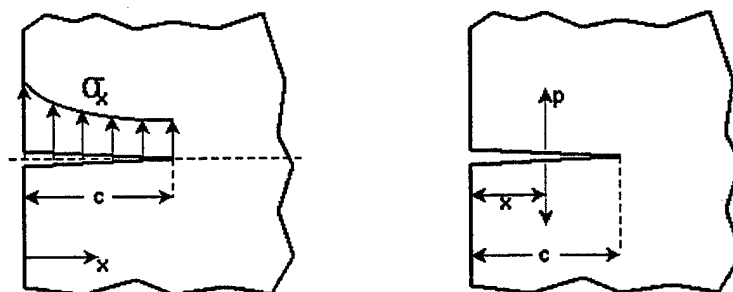


Figure 84: Slope Between Input Data Points

Dividing each stress ratio by the stress ratio at the crack origin normalizes the stress values. This provides a reference for the actual stress at the crack origin. Therefore, the value of the spectrum multiplication factor multiplied by the spectrum stress (or load) values MUST now be the appropriate value at the crack origin.

The normalized stress distribution is integrated using the point load solution as shown in Figure 85.



$$K_I = \sum_{x=0}^c \sigma_x F(c, x) dx$$

$$F(c, x) = \frac{2}{\sqrt{\pi c}} \frac{1.3 - .05(x/c) - .2(x/c)^2 - .3(x/c)^3 + .25(x/c)^4}{\sqrt{1 - (x/c)^2}}$$

Figure 85: Point Load Stress Intensity Solution

The beta correction factor is calculated by dividing the stress intensity determined by integrating the input stress field by the stress intensity value for a unit stress distribution at each crack length increment. Obviously, this method is not exact since it can't account for stress field changes as the crack grows, but it is fairly good - especially at shorter crack lengths where most of the life is spent.

AFGROW multiplies the resulting beta correction factor by the beta factor for the user-selected model at a given crack length. These corrected beta values are printed in the output list in AFGROW in the beta column.

For the [a] crack length dimension: $K_a = \sigma \sqrt{\pi a} \beta_a$

For the [c] crack length dimension: $K_c = \sigma \sqrt{\pi c} \beta_c$

Where, in this case: $\beta = \beta_{\text{model}} * \beta_{\text{correction}}$

In two-dimensional cases, users must refer to the x and y dimensions in the animation frame and the dimensions shown in the beta correction dialog (see Figure 83). The length dimension, r, shown in the dialog box is the radial distance from the crack origin. The input stress ratio values are shown for (r,0) – along the y = 0 axis and (0,r) – along the x = 0 axis.

There are a few important points to remember:

- The stress field is normalized to the stress at the crack origin
- The value of the maximum spectrum stress MUST correspond to the stress at the crack origin
- Choose crack length intervals such that linear interpolation on stress ratio is adequate between points
- When entering stress ratio data for 1-D, values of 1.0 should be input for the other dimensions
- If there is a stress gradient in only 1-D, enter values of 1.0 for all points in the other dimensions
- Accuracy increases with the number of points

3.2.9.2 Enter Beta Correction Factors Manually

Users have the option to enter beta correction factors directly instead of allowing AFGROW to calculate them. There may be cases where a user simply wants to apply beta correction factors that have been obtained from some external source. To enter beta correction factors manually, simply select "Beta Correction Factors" in the "Select Type of Data" section of the beta correction dialog box (see Figure 83).

The beta correction at the crack origin is set equal to 1.0 by default only because the values are required to be normalized at the crack origin when stress values are input. The

beta correction value at the crack origin can only be used as an interpolation limit since all cracks must have a finite length. The first user supplied beta value should be entered for a crack length less than the initial crack size for interpolation purposes. In two-dimensional cases, users must refer to the x and y dimensions in the animation frame and the dimensions shown in the beta correction dialog (see Figure 83). The length dimension, r, shown in the dialog box is the radial distance from the crack origin. The input stress ratio values are shown for (r, 0) along the y = 0 axis (for the width direction) and (0, r) along the x = 0 axis (for the thickness direction). AFGROW will NOT extrapolate beta correction values for crack lengths extending past the input table limits.

3.2.10 Input Residual Stresses

AFGROW can account for the existence of residual stresses by calculating additive residual stress intensities at user defined crack length increments. The dialog shown in Figure 86 will appear when the residual stress option is selected.

Residual Stresses

AFGROW offers the option to model the effect of residual stresses on crack growth by reading in a table of residual stresses as a function of crack length, then AFGROW uses these values to generate a table of 'Residual Stress Intensity Factors' (SIF).

$S(x,y)$ - value of a stress in Z axis direction.
r - distance from the center point of the crack along X or Y axis.

Select type of Data:

☒ Stress ☐ Residual K

Enter stress and r. Use up to 25 sets.

Number of Sets: 6

Set	r	S(r,0)	S(0,r)
1	0	-2.4	-2.4
2	0.02	-1.2	-2.4
3	0.04	0	-2.4
4	0.25	0.55	-2.4
5	0.5	0.5	0
6	1	0.45	0

Generate SIF table using:

☒ Gauss Integration ☐ Weight Function

File:

Open Save

OK Cancel No Stresses

Figure 86: Residual Stress Dialog

Normally, AFGROW does not consider negative values of stress intensity (K) since K is not defined for compression. However, in this application, negative stress intensities can be used since the residual Ks are merely added to the stress intensities caused by the applied loads.

When you use this option, AFGROW will print out the residual K value each time it prints out the standard crack growth information. It is important that you input stress information for the entire range of crack growth since AFGROW WILL NOT extrapolate and will just use the last or nearest applicable value.

Users have the option of entering residual stress values in the crack plane and allow AFGROW to calculate residual stress intensity factors or enter pre-determined residual stress intensity values. When residual stress values are entered, the residual K values may be determined using either the Gaussian integration technique or the weight function method.

3.2.10.1 Determine Residual Stress Intensity Values Using Residual Stresses

There are two methods available in AFGROW to calculate the residual stress intensity values. The first is the Gaussian integration method which uses the point load stress intensity solution from the Tada, Paris, and Irwin Stress Intensity Handbook [54] to integrate a given 2-D unflawed stress field (in the crack plane) to estimate residual K values at user defined crack length increments. The second method uses the weight function stress intensity solutions provided by Prof. Glinka [7].

3.2.10.1.1 Gaussian Integration Method

The Gaussian integration method is the same method that is used to calculate the beta correction factors discussed in section 3.2.9. The only difference is that actual stress intensity (K) values are being calculated instead of a beta correction factor. Stress ratios are NOT used or normalized, since a real K value is being determined. Users should enter the actual residual stress distribution starting at the crack origin. A maximum of 25 points may be input to describe the stress distribution. The intervals should be selected such that linear interpolation would provide a reasonable curve fit between the points. These intervals do NOT have to be uniform, but there should not be a large change in the slope for adjacent intervals. AFGROW uses a Newton interpolation scheme to determine the Gaussian integration points. If the slope change between intervals is large, the code can generate erroneous integration points. AFGROW will provide a warning message if a large slope change is detected (see Figure 84).

There are a few important points to remember for the Gaussian integration method when used to calculate residual K values:

- Choose crack length intervals such that linear interpolation on stress ratio is adequate between points
- When entering stress ratio data for 1-D, input values of 0.0 should be input for the other dimension
- If users only want to show a stress gradient in 1-D for a 2-D case, enter the stress at the crack origin for the second dimension (up to a radial distance equal to the plate thickness) and values of 0.0 for all points in the second dimension beyond the thickness as shown in Figure 86
- Accuracy increases with the number of points

3.2.10.1.2 Weight Function Method

The second method is to use one of the weight function solutions provided through the effort of Prof. Glinka (University of Waterloo, CA). This method will only be possible IF a weight function solution is available for the geometry being analyzed. The currently available weight function solutions are given in section 3.2.3.2. The current weight function solutions ONLY use a stress distribution in a single crack growth dimension. For part-through cracks, the distribution in the thickness direction, and for through cracks the distribution in the width direction is used. In cases where a part-through crack is used, AFGROW will use the distribution in the thickness direction until the crack becomes a through crack and will then switch to use the distribution in the width direction. This makes it less desirable to use the weight function method to determine residual K values for most practical 2-D cases.

3.2.10.2 Enter Residual Stress Intensity Factors Manually

Users have the option to enter residual stress intensity factors directly instead of allowing AFGROW to calculate them. There may be cases where a user simply wants to apply residual stress intensities that have been obtained from some external source. To enter these values manually, simply select "Residual K" in the "Select Type of Data" section of the residual stress dialog box (see Figure 86).

In two-dimensional cases, users must refer to the x and y dimensions in the animation frame and the dimensions shown in the residual stress dialog (see Figure 86). The length dimension, r , shown in the dialog box is the radial distance from the crack origin. The input stress ratio values are shown for $(r, 0)$ along the $y = 0$ axis (for the width direction) and $(0, r)$ along the $x = 0$ axis (for the thickness direction). AFGROW will NOT extrapolate residual K values for crack lengths extending past the input table limits.

3.3 View Menu

The view menu, Figure 87, provides control over what is displayed in the various AFGROW frames.

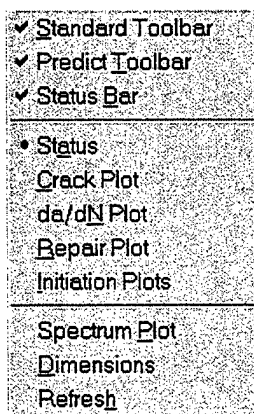


Figure 87: View Menu

The view menu is divided into three sections. The upper section controls the display of the toolbar and status bar. The middle section controls the display of the main frame. The bottom section controls additional special features displayed in the animation frame.

3.3.1 View Standard Toolbar

The standard toolbar, Figure 88, allows a user to perform many common Microsoft Windows® operations:



Figure 88: Standard Toolbar

When selected, the standard toolbar appears in the AFGROW window, and a checkmark appears by this item in the view menu. This toolbar is dockable and can be relocated at the top, sides, or bottom of the AFGROW window. It may also be placed as a floating toolbar anywhere on the desktop. The toolbar is moved by placing the mouse pointer in a blank area between two icons, holding down the left mouse button, and dragging the toolbar to the desired location.

The function of each icon is displayed through the standard Windows help when you move the mouse over the icon.

3.3.2 View Predict Toolbar

The predict toolbar, Figure 89, allows a user to use shortcuts to perform many common operations required to perform crack growth life predictions:



Figure 89: Predict Toolbar

When selected, the predict toolbar appears in the AFGROW window, and a checkmark appears by this item in the view menu. This toolbar is dockable and can be relocated at the top, sides, or bottom of the AFGROW window. It may also be placed as a floating toolbar anywhere on the desktop. The toolbar is moved by placing the mouse pointer in a blank area between two icons, holding down the left mouse button, and dragging the toolbar to the desired location.

The function of each icon is displayed through the standard Windows help when you move the mouse over the icon.

3.3.3 View Status Bar

The status toolbar is found in the margin at the bottom of the output frame (see Figure 20).

The purpose of the status toolbar is to provide additional information related to a given analysis. The status bar is a tool that Microsoft provides and should not be confused with the "status view" which is used by AFGROW to display the current input data in the upper left window. For more details, refer to section 2.6.

3.3.4 View Status

The status window is one of the optional "windows" which may be displayed in the upper left-hand window (main frame) in the AFGROW main window (see Figure 9).

The window may be displayed by clicking on the view, status menu buttons on the main AFGROW menu OR by simply using the pull-down menu in the upper left-hand AFGROW window. For more details, refer to section 2.1.1.

3.3.5 View Crack Plot

The crack length plotting capability allows a user to graphically examine the crack growth life predictions being performed by AFGROW in real time (see Figure 11). When selected, a new menu item (Plots) will appear in the menu bar. This menu item provides access to the same features given in the rebar tool in the main frame. For more details, refer to section 2.1.2.

3.3.6 View da/dN Plot

The da/dN plotting capability allows a user to graphically examine the crack growth rate properties to be used by AFGROW (see Figure 13). When selected, a new menu item (da/dN Plots) will appear in the menu bar. This menu item provides access to the same features given in the rebar tool in the main frame. For more details, refer to section 2.1.3.

3.3.7 View Repair Plot

The repair plotting capability allows a user to graphically examine the beta correction plots for up to eight repair designs (see Figure 14). For more details, refer to section 2.1.4.

3.3.8 View Initiation Plots

The initiation plotting capability allows a user to graphically examine the cyclic stress-strain and strain-life plots for the current input data (see Figure 15). When selected, a new menu item (Initiation Plots) will appear in the menu bar. This menu item provides access to the same features given in the rebar tool in the main frame. For more details, refer to section 2.1.5.

3.3.9 View Spectrum Plot

The da/dN plotting capability allows a user to graphically examine the spectrum being used by AFGROW (see Figure 90).

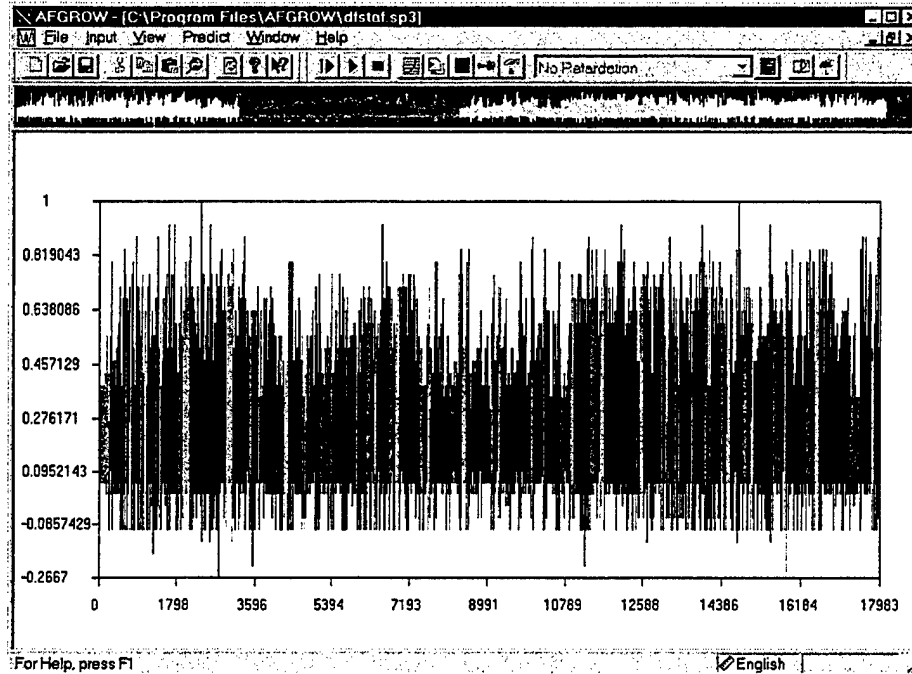


Figure 90: Spectrum Plot

When this option is selected, a new spectrum window will be created. While in this view, several tools in the toolbar are now grayed out since they serve no purpose in the spectrum view window. The color of the data plotted is changed for each sub-spectrum.

Users can zoom-in the spectrum view by using the mouse and dragging out the area to view on the spectrum plot. The entire spectrum is always displayed in the upper area of this view. Users can also adjust the view in the upper area of the window by using the mouse and dragging the highlighted box.

3.3.10 View Dimensions

The Dimensions option in the View menu simply shows the definition of the basic geometric dimensions for the current model being analyzed. For example, the corner cracked hole dimensions are shown in Figure 91.

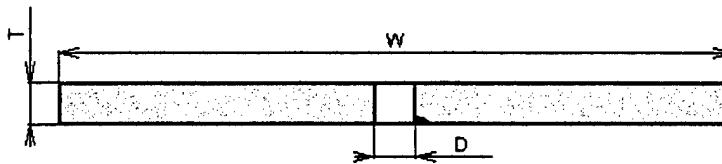


Figure 91: Specimen Dimensions

The specimen dimension display is turned on and off by selecting this menu item. A check mark is displayed beside this menu item when the dimensions are being displayed.

3.3.11 View Refresh

The Refresh option in the View menu simply resets the initial crack dimensions in the model being analyzed. Once an analysis is performed, the final crack size is shown in the upper right window. The refresh option will reset the image to show the initial crack dimension(s)

3.4 Predict Menu

The predict menu, Figure 92, controls options related to life prediction.

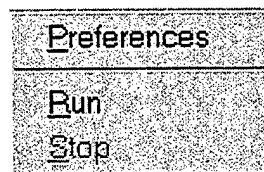


Figure 92: Predict Menu

3.4.1 Predict Preferences

The preferences menu selection is one of the most important menu items in AFGROW. There are several optional settings which may be changed to suit the various requirements of a given life prediction. The preferences are divided into five categories and are accessible through a tabbed dialog box as shown in Figure 93.

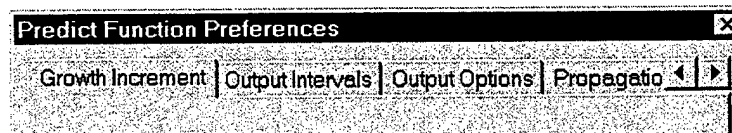


Figure 93: Preference Categories

The preferences dialog is accessible through the AFGROW menu OR by right clicking anywhere in the output frame. The user sets the preference options with the buttons shown in Figure 94.



Figure 94: Saving and Restoring Preferences

Use the Save button to save all parameter settings. These settings will be retained until changed by the user. The Default button will return the original AFGROW preference settings.

3.4.1.1 Growth Increment

AFGROW allows users to set the crack growth increment for use in calculating the current stress intensity as indicated in Figure 95.

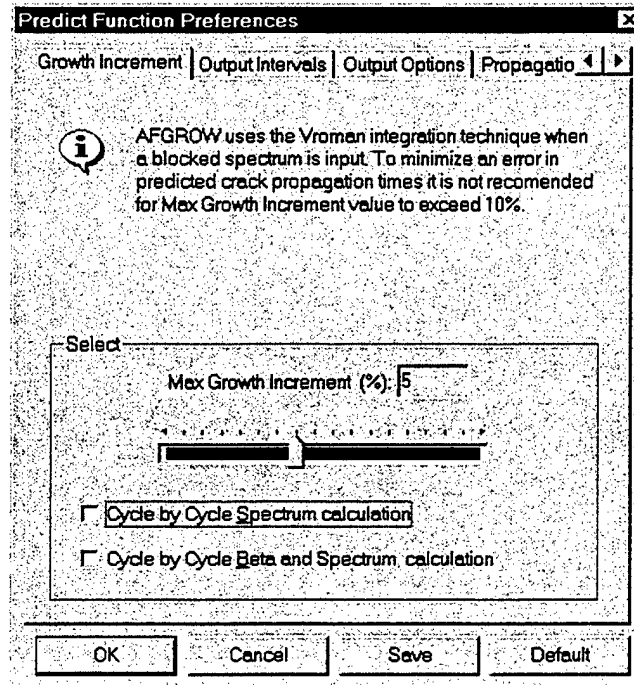


Figure 95: Growth Increment Dialog

The increment is used to determine the maximum number of cycles in a given spectrum level which may be used before the stress intensity values must be recalculated. A “blocked” spectrum is a spectrum that has been simplified to consist of stress (or load) levels, which may have more than one cycle. Since crack growth per cycle is NOT linear, stress intensity and crack growth rates MUST be recalculated at some crack length increment. This option is designed to give the user more control over an analysis. There is a direct trade-off between speed of calculation and accuracy. Higher increments reduce runtimes, but also decrease accuracy.

The increment value is also important when a “cycle-by-cycle” (1 cycle per stress level) spectrum is used. The increment ALSO controls how often AFGROW runs the internal routine to determine the alpha (α) values that are used to determine stress intensity. These alpha routines can be very CPU intensive and this control also provides the same kind of trade-off of speed and accuracy noted above. The following definitions are important for a good understanding of how this works in AFGROW:

$$K = \sigma \alpha$$

$$\alpha = \beta \sqrt{\pi x} ; \text{ Where } x = \text{crack length}$$

In addition to controlling how blocked spectra are analyzed, AFGROW currently allows users to control how often beta factors are calculated based on a percentage of crack length. The limits are from 0.25 to 15 percent of a given crack length. Increasing this percentage may reduce run times; however, the speed is traded for life prediction accuracy.

The cycle-by-cycle spectrum option allows the increment to be adjusted from 0.25 to 5 percent. The alpha values are calculated based on the selected increment, but the betas are adjusted (from the alphas) for crack length on a cycle by cycle basis. The current cycle-by-cycle beta option is a TRUE cycle-by-cycle alpha, beta, and spectrum calculation. Run times may be significantly increased when using this option. If neither option is selected, the allowed increment range will be from 0.25 to 15 percent.

One question that is sometimes asked is "Why does a crack growth plot sometimes appear somewhat jagged even when a constant amplitude spectrum is used?" This is caused when an increment is used which is too large to give an accurate answer. This "jagged" plot will be smoothed by reducing the increment or essentially eliminated by using the cycle-by-cycle beta option. However, it should be noted that a random stress spectrum would tend to produce a "jagged" crack growth curve due to the fact that the stress (or load) levels are changing.

3.4.1.2 Output Intervals

The printing interval for output data is controlled by the Output Interval dialog (see Figure 96).

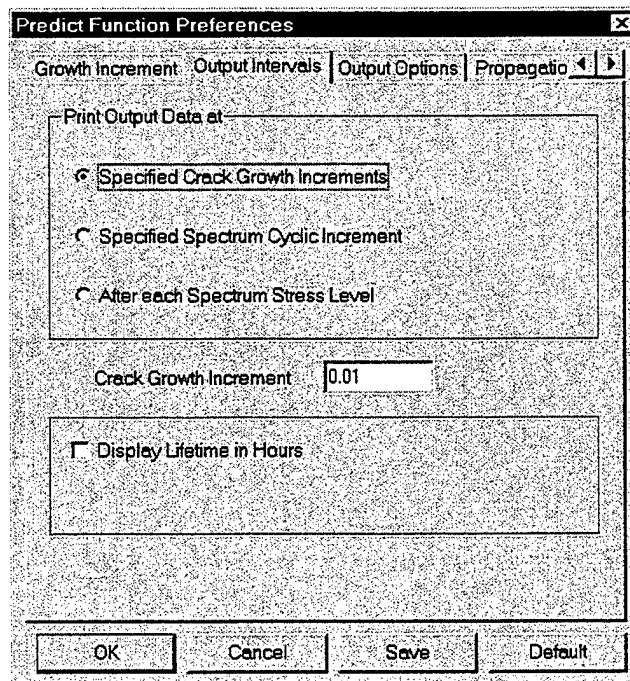


Figure 96: Output Interval Dialog

The crack growth or cyclic options will prompt the user to input the numeric value for the appropriate interval. The option to print after each Spectrum Stress Level is provided for debugging or error checking purposes and can result in a LARGE amount of data.

The option to display the lifetime in hours is merely a conversion from spectrum passes to hours, which is printed at the end of the output file. The plot file will have a column that will be converted to hours for plotting purposes.

3.4.1.3 Output Options

Users may select different output file options as indicated in Figure 97.

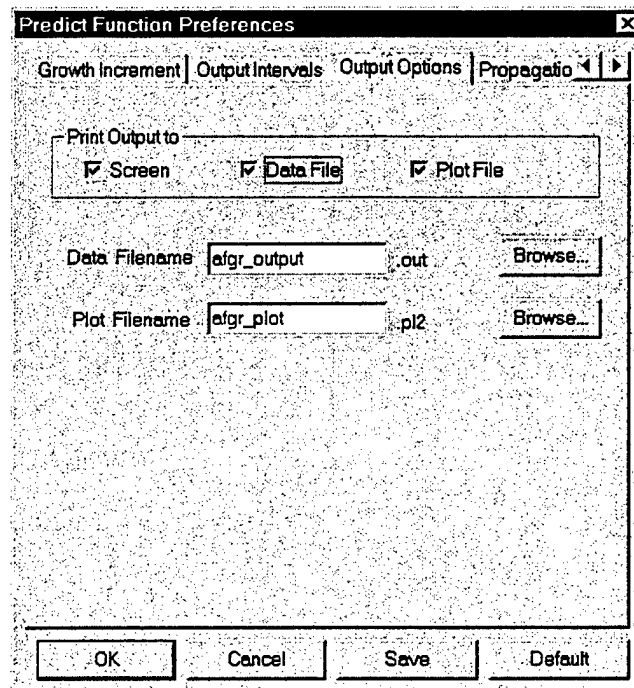


Figure 97: Output Options Dialog

The default option is the Screen, which prints the output data to the output frame in the AFGROW window. The Data File option allows a user to write the output data to a user specified file. The file may be printed or merely saved as a record of a given analysis. The Plot File option is used to create a file containing crack length, beta, and spectrum cycle data that may be plotted in Excel or other plotting software. It should be noted that the Plot File option **MUST** be selected in order to use the option in the Tools menu to export plot data to Excel.

When the Data File or Plot File options are selected, a default filename will appear in the appropriate text window. If the default filename is not changed, AFGROW will **OVERWRITE** any existing default file. If a user types any other filename, AFGROW will display a **WARNING** dialog **BEFORE OVERWRITING** an existing file with the same name.

AFGROW prints three different R-values in the Screen and Data File output. An example of the screen output is given in Figure 98.

```
C Crack size= 0.21 Beta= 1.006 R(k)= 0.267 R(ef)= 0.267 Delta k=1.252e+001 D0/DN=1.007e-005
Max stress = 20.915 r= 0.27 162446 Cycles Flight: 1806 Pass: 10

C Crack size= 0.22001 Beta= 1.007 R(k)= 0.076 R(ef)= 0.076 Delta k=1.539e+001 D0/DN=1.379e-005
Max stress = 19.892 r= 0.08 180635 Cycles Flight: 2010 Pass: 11

C Crack size= 0.23 Beta= 1.007 R(k)= 0.331 R(ef)= 0.331 Delta k=4.373e+000 D0/DN=1.621e-007
Max stress = 7.635 r= 0.33 197380 Cycles Flight: 2197 Pass: 11
```

Figure 98: Sample Output Data

The value (r), which is printed next to the Max stress value, is the ratio of the minimum to maximum applied stress (or load) for the current spectrum cycle. The value (R(k)) is the ratio of the minimum to maximum stress intensity values which are calculated for the current cycle AFTER the load interaction model is applied. This value ALSO includes the effect of residual (additive) K values caused by residual or thermal stress effects. The value (R(ef)) is the ratio of the minimum to maximum stress intensities determined in the crack growth rate routine. This value is used with the printed value of Delta K to determine the appropriate crack growth rate. These values are printed to provide the information needed for a user to verify that the appropriate crack growth rate is being calculated for the options selected for a given analysis.

If a user chooses a value for Rlo or Rhi that does not cover the actual applied stress ratios in a given spectrum, the value of R(ef) will show this limitation when compared to r and R(k).

Note: Since the definition of Delta K for $R(ef) < 0.0$ depends on the crack growth rate model, the definition of Delta K is printed in the output data in the section where the crack growth rate model is printed. Also, if the Wheeler retardation model is used, remember that this model uses a "knock-down" factor on crack growth rate to affect the retardation.

3.4.1.4 Propagation Limits

AFGROW allows the user to set crack growth propagation limits on life analysis as indicated in Figure 99.

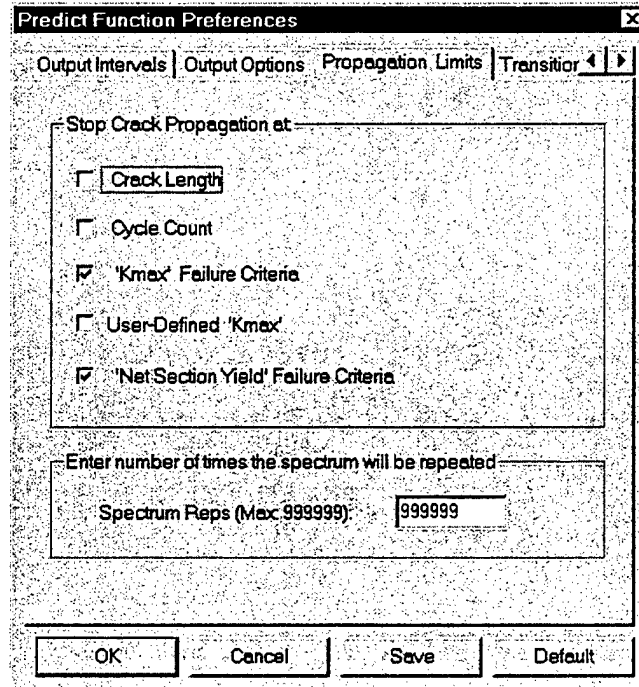


Figure 99: Propagation Limits Dialog

When selected, AFGROW will terminate at the first instance of any selected limit. When a limit is selected which requires additional input, AFGROW will open the appropriate input box for data entry.

Note: In the case of the net section yield criteria, the net section stress is based on the remote tensile load and the net area in the crack plane (minus the yield zone).

Bearing load is assumed to be uniformly distributed through the net section and is determined as:

$$\text{Bearing Load} = \text{Bearing Stress} * \text{Hole Diameter} * \text{Thickness}$$

For cases that include out-of-plane bending, it would be far too conservative to use the bending stress value (taken at the plate surface). In this case, the tensile stress due to the bending at 1/6 of the thickness is substituted. This is the centroid of the tension stress due to the out-of-plane bending. The only exceptions to this are the rod and pipe geometries since the calculations are very complex since the change in moment of inertia would have to be recalculated as the crack grows. At this time, out-of-plane bending is ignored for these geometries in terms of net section stress.

AFGROW does not include any contributions of crack asymmetry to in-plane bending contributions to the net section stress. Although it is possible for in-plane bending to play a role in the true net section yielding, there are usually geometric constraints that will prevent or mitigate this effect.

3.4.1.5 Transition Options

AFGROW allows the user to set the part through to through-the-thickness crack transition criteria as indicated in Figure 100.

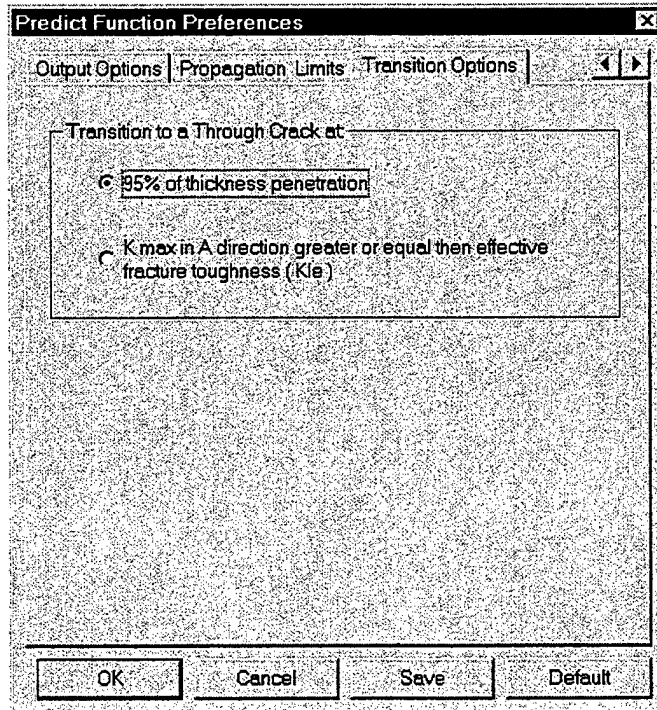


Figure 100: Transition Options Dialog

These criteria control when a part-through crack becomes a through-the-thickness crack. The default transition criterion is 95 percent thickness penetration. When the a-dimension reaches 95% of the thickness (or 2a for surface or fully embedded cracks), the crack is assumed to become a through-the-thickness crack.

The alternative criterion is the K_{Ie} method. This has been used in NASGRO based on observations that transition may occur if the maximum stress intensity value in the a-direction exceeds a prescribed value. This value is called K_{Ie} (equivalent fracture toughness for a part-thru crack). Values of K_{Ie} are included in the NASGRO material database. Typically, K_{Ie} may be estimated as:

$$K_{Ie} = 1.4(K_{Ic})$$

K_{Ic} is (of course) the plane strain fracture toughness for a given material. Therefore, if the NASGRO material database is NOT used, K_{Ie} will be estimated as shown above.

3.4.2 Predict Run

Toolbar Icon:



This option will start the AFGROW life prediction process.

3.4.3 Predict Stop

Toolbar Icon:



This option will stop the AFGROW life prediction process.

3.5 Tools Menu

Access to other software tools is available through the tools menu. These tools enhance the capabilities of AFGROW in several areas: viewing plots in Excel, spectrum translation, and interfacing with an aging aircraft structures database.

3.5.1 View Plots in Excel

AFGROW allows plot files to be written directly to Microsoft Excel. At this time the feature ONLY works with Excel for Win95 (Excel7), 97 (Excel8), or Excel for Office 2000. When this option is selected, the Open Excel dialog appears (see Figure 101).

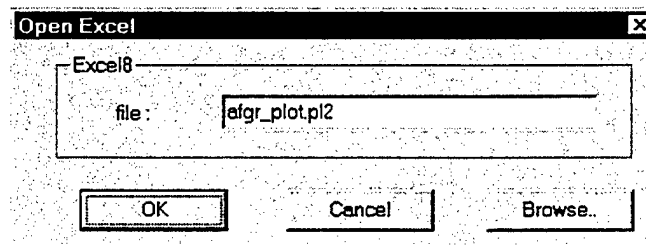


Figure 101: Dialog Box to View Plots in Excel

The default plot file name will appear in the dialog box. The user may enter the desired file name manually by clicking inside the text box, or may browse the computer to find the desired plot file.

Once started, AFGROW opens Excel on the users PC and writes the data to Excel. The crack length vs. cycle data will be plotted on separate worksheet(s). The speed at which this happens will, of course, be dependent on the PC. Once this is complete, users can work with the Excel file as desired. For more details on creating a plot file, see section 3.4.1.3.

3.5.2 Aging Aircraft Structures Database (AASD)

AFGROW provides a link to an Aging Aircraft Structures Database (AASD) program developed by Boeing/St Louis (Dr. Rigoberto Perez and Mr. Michael VanDernoot) under contract to the US Air Force [55]. A sample screen shot of AASD is shown in Figure 102.



Figure 102: Aging Aircraft Structures Database

The AASD allows users to examine actual maintenance details and copy the crack data into the Windows clipboard for use in AFGROW. The AASD menu in AFGROW offers the following commands:

- Run - Run AASD
- Paste - Paste data from AASD to AFGROW

Once the data are pasted into AFGROW, life predictions may be performed to estimate the life of a given component or to verify an analysis (if sufficient verification data are available in AASD).

This database provides detailed crack length, material and spectrum information for several current Air Force aircraft. The distribution of AASD may initially be limited. Requests to obtain a copy of AASD may be made through the Air Force (use the Mail command from the File menu). If AASD is not installed, this menu selection will be grayed out.

3.5.3 Run Spectrum Translator

AFGROW includes a spectrum translation program, Figure 103, which will convert many existing stress (or load) spectra to the format needed in AFGROW. This program is written and maintained by the developers of AFGROW (AFRL/VASE).

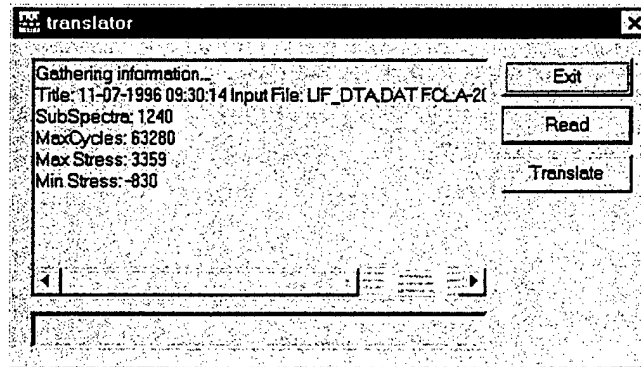


Figure 103: Spectrum Translator

Currently, the following spectrum formats may be translated:

- Supercracks
- Cracks 3
- NORCRAK
- Cracks95

Once the spectrum has been read and analyzed, press the Translate button to finish the translation. The file names (filename.sp3 and filename01.sub) of the translated spectrum will be the same as the original file.

Other spectrum formats may be translated upon user request.

3.5.4 Run Cycle Counter

A cycle is defined as shown below in Figure 104. A cycle begins at a certain stress (or load) level, moves to a different level, and returns to the starting level.

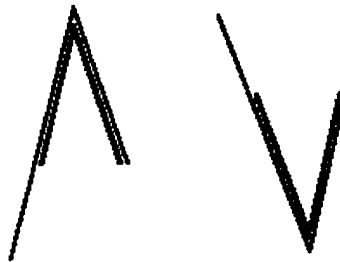


Figure 104: Cycle Definition

Many people have submitted questions related to how AFGROW uses the input spectrum data. Each line in an AFGROW spectrum consists of one or more cycles. A cycle is described by any two of the following parameters: minimum value, maximum value, or stress ratio (R). It makes no difference which two parameters are used, or what order they are listed.

Real structures are loaded and unloaded periodically so that the peak-valley sequence of applied stresses is unlikely to form true cycles. The actual peak or valley points are often

referred to as reversals since the loading direction (increasing or decreasing) is reversed at each point (see Figure 105).

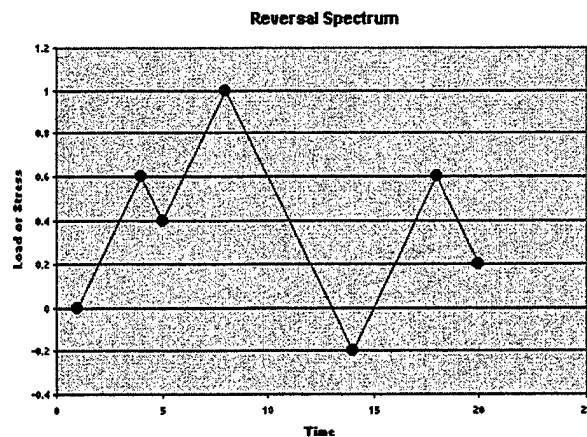


Figure 105: Sample Uncounted Stress Sequence

In any case, the important fact is that AFGROW assumes that the input spectrum is given in the form of cycles, not simply an uncounted sequence.

AFGROW provides a cycle counting program [XX] than can be used to convert uncounted sequences to cycles (see Figure 106). This tool is provided for the convenience of our users, but there are other cycle counting methods in the open literature that may be used as desired.

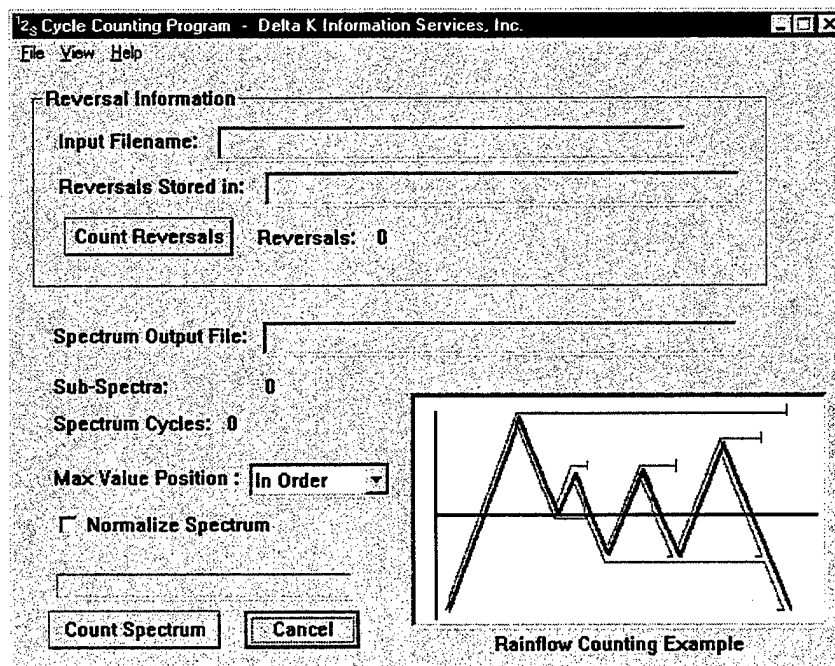


Figure 106: Cycle Counting Software Interface

This program has many features, which are described in detail in its own on-line help. The program will convert stress values to reversals and reversals to cycles. If reversals are available, they can be used as is to create the counted spectrum.

An important point to note is the placement of the maximum value in the spectrum. The cycle counting program will place counted cycles in the order determined by the order of the peak points. Some fracture mechanics experts prefer to place the overall maximum value at the end of the spectrum to minimize the effect on crack growth retardation (more conservative result). Others may prefer to place the maximum peak in the order that the peak occurs in the original sequence. There is an option to place the maximum value at the beginning, end, or in the original order of the peak values.

The resulting spectrum may be normalized so that the maximum value is 1.0. This is very common and allows users to scale the spectrum values based on the overall maximum value - without using a calculator.

Finally, it is important to know whether or not a spectrum has already been cycle counted. Generally, spectra created for crack growth life prediction will be counted. It is not easy to tell, so it is important to find out. If a counted spectrum is counted twice, it will be altered (unless it is a constant amplitude sequence). The initiation module in AFGROW assumes the spectrum is also counted (see section 3.7). It would have been very difficult to manage both counted and uncounted spectra in AFGROW. In short, if you are using a spectrum in AFGROW, it had better be cycle counted.

3.6 Repair Menu

AFGROW includes an option to account for the effect of a bonded repair patch on crack growth life. This analysis is based on a Green's function method and was developed by Dr. Mohan Ratwani [7]. Currently, this method is only valid for the following conditions:

- Through the thickness cracks
- Thin structure (< 0.125 in.)
- Non-stiffened panels
- Crack remains under the patch

The stress intensity solution is determined by integrating the 2-D adhesive shear stresses in an area surrounding a centered through crack in an infinite plate. This area is simulated using a telescopic grid with a fine mesh covering the crack and a course mesh extending a distance of one half of the total crack length on either side. The height of the mesh extends to one and a half of the total crack length above and below the crack. Due to symmetry conditions, a quarter of the panel is analyzed with a total of 144 nodes. A unit stress is applied to the cracked panel and stress intensity values are determined for approximately 20 crack lengths (crack intervals are calculated using an algorithm in the model). The initial crack length is the same as the initial crack length specified by the user and the final crack size (c) does not exceed 2 inches. A beta correction table is generated by dividing the stress intensity for the patched case by the stress intensity for the same case without a patch. The correction for cracks exceeding 2 inches is assumed to be constant⁷. The assumption is that a centered through crack solution is used to determine the beta correction due to the bonded repair at various crack lengths and is applied to the actual geometry selected by the user. The 2-inch limit on the beta correction values is based on analysis and test verification data. These data indicate that the ratio of the patched to non-patched stress intensity values tend to be nearly constant above a half crack length (c) of 2 inches for the center cracked case using typical patch materials and adhesives.

AFGROW will store up to eight repair designs and their beta correction tables. The most current design is active by default, but the user may change the active design through the repair plot option in the view window or menu selection.

The repair menu options are described in the following sections.

3.6.1 Repair Design

When the repair design is selected, AFGROW will not allow certain values to be changed for the given crack model. The reason for this is that material properties and model dimensions are required for the repair analysis. If any of these values were changed, the

⁷ The stress intensity value will NOT be constant, only the beta correction value which is multiplied by the stress intensity value for the non-patched case

repair analysis would have to be redone. A dialog will appear informing users of this situation.

A wizard is used to guide users through the repair design process as described in the following sections.

3.6.1.1 Ply Design and Lay-up

Ply Design and Layup

Material Properties

Name: GRAPHITE/EPOXY

Id	Value	Description
EL	25000	Youngs ...
ET	1500	Youngs ...
GLT	700	Shear M...
PNU	0.3	Poisson ...
ALFL	-4e-007	Coef. of ...
ALFT	2e-005	Coef. of ...

Change Material Database File

Number of Plies: 13

Ply Thickness: 0.0052

Delta T: 0

Ply Layup:

Orient.	Ply #
45	1
-45	2
0	3
0	4
90	5
0	6
0	7
0	8
90	9
0	10
0	11
-45	12
45	13

Patch Type

Number of Plies is half the total numbers of plies for symmetric patches

☐ Symmetric

☐ Double_Sided

☐ No Bending

Patch Stiffness Indicator(% of Plate Stiffness)

70% 100% 120% 150%

Out of bounds Allowed Ideal Allowed Out of bounds

Auto Design < Back Next > Cancel Help

Figure 107: Ply Design and Lay-up Dialog

This dialog contains the information for the repair patch including whether to consider out of plane bending and an option to consider thermal residual stresses in the stress intensity solution. The repair design is performed automatically using an internal algorithm based on the maximum applied stress and the modulus of the cracked plate. The automatically generated ply lay-up includes cross plies to provide delamination resistance. In addition, Dr Ratwani's method tends to produce errors if the patch moduli in the x and y directions differ greatly. For these reasons, cross ply lay-ups are preferred. The load direction is assumed to be normal to the crack plane. Users can make any desired changes to the design by making changes to the material properties, ply lay-up, or type of patch.

3.6.1.1.1 Material Properties

The material properties are given for the appropriate material in the default database file. The user MAY NOT change these values since they are interrelated. The use of invalid

composite material properties will cause the analysis to crash. Users may create their own material database files⁸, but must be sure to input valid property values.

The user has control over the number of plies, ply thickness, and Delta T. The Delta T parameter (degrees F) is included to provide a means to account for the residual thermal stressed caused by the differences between the thermal expansion of the cracked plate and composite patch. Some believe that Delta T should be the difference between the patch curing temperature and the operating temperature. Others think that there may be some relaxation in the adhesive after curing which results in a lower effective Delta T. In any case, the user is free to use judgment in setting this value.

3.6.1.1.2 Ply Lay-up

The ply lay-up is initially determined by AFGROW based on a criterion to include cross plies for some biaxial strength, symmetry, and a target value of patch stiffness of 110 percent of the cracked plate stiffness. The user may change the lay-up⁹ by using the mouse to either drag a ply to a new location or selecting a ply (single click) and touching the control key (or a second, single mouse click after a few second pause). AFGROW also includes an option to auto design the ply orientation (left click in the Orient... button) and an auto design option for both the orientation and number of plies (left click in the Ply # button). Cross ply lay-ups are desirable to help prevent the patch from delaminating during normal use. Also, it should be noted that Dr. Ratwani's method has been known to have problems if the patch E_x and E_y values differ by large amounts (i.e.: uniaxial lay-up).

3.6.1.1.3 Patch Type

The three options for patch types are:

Symmetric: The ply lay-up shown is doubled and the lay-up is therefore symmetric with respect to the center of the patch.

Double Sided: The patch is applied on both sides of the cracked plate (eliminates out of plane bending for symmetric patches).

No Bending: Do not account for out of plane bending in the calculations. The plate may be constrained to prevent bending or the user may wish to compare the results with and without out of plane bending.

⁸ The data in the material database file must be in English units. AFGROW will make the appropriate conversion based on the current units being used.

⁹ The maximum number of allowable plies in the current version is 32 (16 if the symmetric option is active).

3.6.1.1.4 Patch Stiffness Indicator

The patch stiffness indicator allows the user instant feedback on the patch design. The target is 110 percent of the plate stiffness to provide strength to help keep the crack closed, but not so stiff to attract too excessive load to the patch. Remember that this is calculated based on thickness and is independent on the patch width. Where possible, it is recommended that the patch width be twice the width of the crack over the projected life of the repair.

3.6.1.2 Patch Dimensions and Adhesive Properties

This dialog, Figure 108, contains the information for the repair patch dimensions and adhesive properties. This includes modeling the local disbond in the adhesive, which tends to occur around a cyclically loaded crack. There is also an option to control whether the patch is considered when using the critical stress-intensity factor failure criterion.

Patch Dimensions and Adhesive Properties

Sample C-Scan image of a repair:

Adhesive Properties:

Name: FM-73

Shear Modulus (GXY): 60

Thickness: 0.006

Disbond (Dh/C): 0

Patch Dimensions:

Width (Wp): 4

Length (Lp): 4

Critical SIF based on:

☒ Patched Structure

☐ Unpatched Structure

< Back Next > Cancel Help

Figure 108: Patch Dimensions and Adhesive Properties Dialog

3.6.1.2.1 Sample C-Scan Image of a Repair

The sample C-Scan image (see Figure 108) is provided to show the patch dimensions and explain the concept of the adhesive disbond, which normally occurs around the crack tip under cyclic loading. The method, proposed by Dr Ratwani, assumes the disbond follows the crack tip and is elliptical in shape.

3.6.1.2.2 Adhesive Properties

The adhesive properties consist of the following:

Name: Adhesive name (for documentation purposes)

Shear Modulus (GXY): Adhesive shear modulus

Thickness: Thickness of adhesive layer

Disbond (Dh/C): Ratio of minor to major axis of an assumed elliptical disbond at the crack. Of course, zero indicates that there is no disbond.

3.6.1.2.3 Patch Dimensions

The current solution provided by Dr Ratwani assumes the patch to be twice the width of the crack. However, verification tests have shown that the solution provides reasonable results for cracks extending to the edge of the patch¹⁰. The only purpose for the user input patch width is for the out of plane bending calculations.

Width (Wp): Patch Width (in.)

Length (Lp): Patch Length (in.) - At this time this variable is not used in the analysis; however, the patch length is assumed to be infinite in the analysis at this time.

3.6.1.2.4 Critical SIF

The critical stress intensity factor may be based on either of the following:


Patched Structure: The critical stress intensity factor calculation includes the patch beta correction factor.

Unpatched Structure: The critical stress intensity factor calculation DOES NOT include the patch beta correction factor. All this does is allow a user to be a bit more conservative in the life prediction. Of course, this conservatism is only valid if you assume the patch would fall off AFTER the crack is EQUAL to or LARGER than the critical crack size without a patch.

¹⁰ In cases where the crack is longer than one half the patch width, AFGROW sets the adhesive shear stress values to zero for nodes that fall outside the patch boundary when calculating the beta correction values.

3.6.1.3 Designed Patch Properties

This dialog, Figure 109, shows the ply lay-up and resulting laminate structural properties.

Designed Patch Properties	
Ply Orientations <div style="display: flex; align-items: center;"> <div style="text-align: right; padding-right: 10px;"> 45.0 +0.0 +0.0 +0.0 +0.0 +0.0 -45.0 </div>  <div style="text-align: left; padding-left: 10px;"> +45.0 +0.0 +90.0 +0.0 +90.0 +0.0 +45.0 </div> </div>	
Patch Properties Name: GRAPHITE/EPOXY	
Youngs Modulus in X Dir. (EX):	15400.3886718
Youngs Modulus in Y Dir. (EY):	6708.38
Shear Modulus (GXY):	2464.54
Thickness (THICK):	0.0676
XY Poisson Ratio (NUXY):	0.316096
YX Poisson Ratio (NUYX):	0.137691
Coef. of Thermal Exp. in Y:	1.3414e-007
Coef. of Thermal Exp. in X:	2.87297e-006
Width (Wp):	4
Length (Lp):	4

Save
< Back
Next >
Cancel
Help

Figure 109: Patch Dimensions and Adhesive Properties Dialog

Ply Orientations: This window simply shows the ply orientation of the complete patch.

Patch Properties: The patch properties are given for the total patch laminate.

Save Button: The complete repair design may be saved to a file for later use.

At this point, clicking on the NEXT button will start the repair analysis. This can take a few minutes (depending on the computer) and a progress bar will appear to give an indication of the expected run time.

Once the analysis is complete, the repair beta correction vs. crack length plot is displayed, as shown in Figure 110.

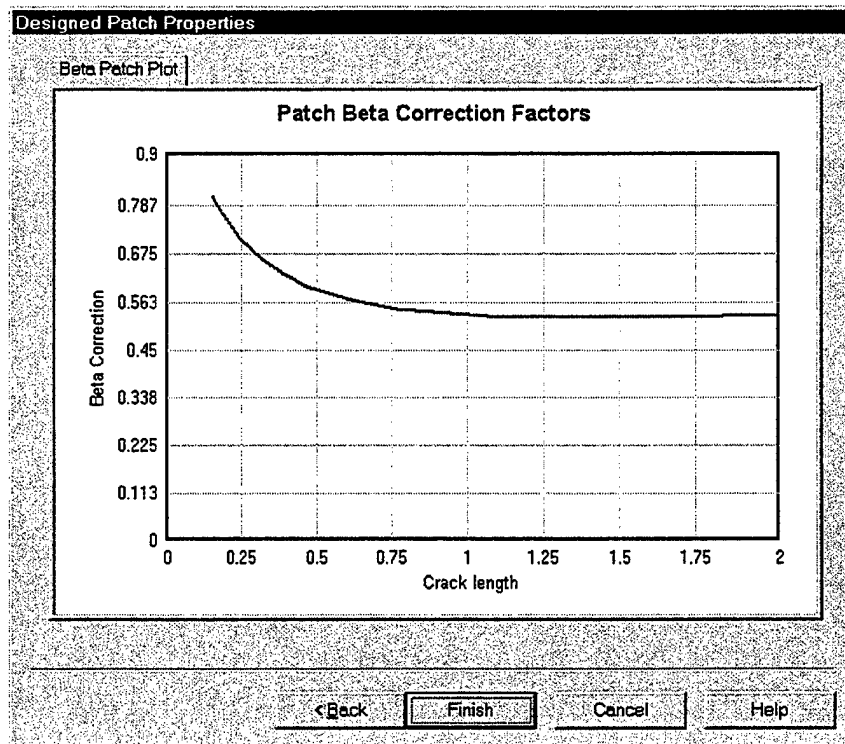


Figure 110: Repair Beta Correction vs. Crack length

Users may accept the design by clicking on the “Finish” button or return to the repair design wizard by clicking on the “Back” button. If the “Finish” button is selected, the specimen cross-section view in the animation frame is shown with a depiction of the bonded repair (see Figure 111).

Center Through Crack - Standard Solution



Figure 111: Specimen Cross Section View with a Bonded Repair

3.6.2 Read Design Data

This option opens a file containing data for a previously saved repair design (see section 3.6.1.3). The file dialog is shown in Figure 112.

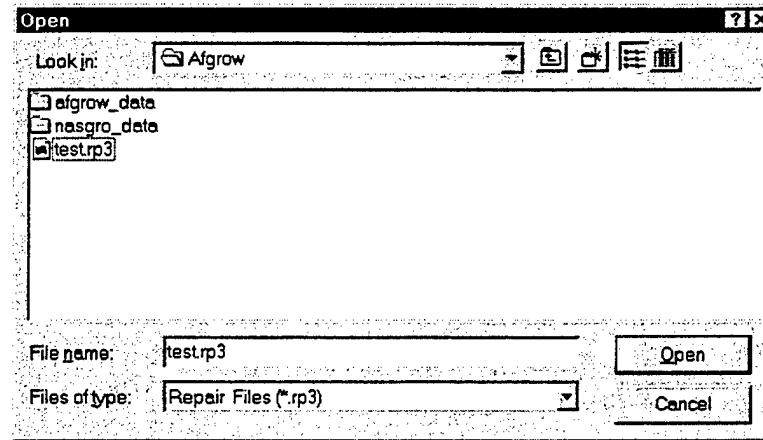


Figure 112: Opening a Repair Design File

3.6.3 Repair/No Repair

This option simply activates/deactivates the repair so a user may perform a crack growth analysis for the same case with or without the effect of the bonded repair. If a repair is active, this menu item is shown as “No Repair” and will deactivate the current repair design if selected. If the repair is not active, this menu item is shown as “Repair” and will activate the current repair. This may be useful when comparing the analytical results with and without the effect of the repair patch.

This option will NOT delete the patch.

3.6.4 Delete Repair

This option WILL delete the patch. This is required if you wish to change the material properties or geometry of the repaired structure¹¹.

3.7 Initiation Menu

Eric Tuegel (AP/ES, INC.) initially provided the strain-life based fatigue crack initiation module used in AFGROW [8]. The original module was written in Visual Basic for Applications (Excel Macro). This code was converted to the C/C++ language and a visual interface was added to make the code easier to use.

¹¹ AFGROW will not allow a user to change certain properties while a repair beta correction table is being used.

In addition, it should be noted that the original module assumed the input stress spectrum was a peak/valley, uncounted spectrum. Uncounted stress spectra consist of peaks and valleys that are not arranged (counted) such that each peak/valley pair defines a closed hysteresis loop (see Figure 120). Since counted spectra are required for crack growth life prediction, this module was modified to accept cycle counted spectra. Each cycle is assumed to lie on the tension side of the overall hysteresis loop for the maximum and minimum values in the spectrum. This should provide conservative results since the mean stress for any cycle will be greater than or equal to the corresponding case for an uncounted input spectrum.

3.7.1 Strain-Life Initiation Methodology

The module uses standard strain-life methods including:

- Neuber's Rule
- Smith-Watson-Topper Equivalent Strain
- Fatigue Notch Factor (K_f)

The first important point to make about this implementation is that it was designed to work in conjunction with the rest of AFGROW as an additional capability. When used, it will provide an initiation prediction (cycles) which will be added to the cycles calculated for subsequent crack growth life. The flaw size after initiation is assumed to be equal to the initial crack size that was input in the model dimensions dialog (see Figure 58, section 3.2.3.4). This provides additional flexibility since a user can use any initial crack length, which is felt to be best for the given input crack initiation data. Note that AFGROW will simply determine the initiation life based on the input data provided and add the initiation life to the crack growth life from the initial input crack size.

It should also be noted that the initiation module should ONLY be used in cases where there is a notch or hole. Since the code uses Neuber's rule, input data obtained using smooth bar specimens will not return accurate results if K_t is set equal to 1.0. It is possible to model a notch case using an un-notched model as long as the appropriate K_t , notch radius, and fatigue notch constant are used.

Another item worth noting is the fact that Young's modulus (E) is part of the material data associated with the crack growth rate data. Young's modulus is required for the initiation module, but it would be a bad idea to have the same parameter in two different dialog boxes. It is important to be sure that the modulus is correct for the given model when any changes are made to the initiation parameters. This will show up graphically in the cyclic stress-strain curve in the initiation plot option in the main frame (see Figure 15, section 2.1.5).

3.7.1.1 Neuber's Rule

Neuber's equation [55] may be expressed in the following form:

$$\frac{(K_f \Delta S)^2}{(4E)} = \frac{\Delta \sigma \Delta \epsilon}{2}$$

Where S is the applied stress and σ and ϵ are the resulting local stress and strain values corrected for the notch effect.

Since the local corrected stress and strain values are two unknown values; the input material cyclic stress strain curve is used in conjunction with Neuber's equation to determine these values as indicated in Figure 113.

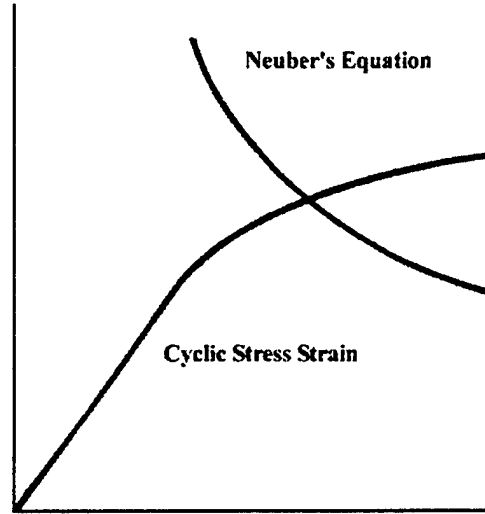


Figure 113: Neuber's Rule

3.7.1.2 Smith-Watson-Topper Equivalent Strain

Normally, strain-life data are available for the case of fully reversed loading ($R = -1.0$). In order to account for the effect of load cycles that are not fully reversed, an equivalent applied strain must be determined for each cycle in the applied spectrum. The Smith, Watson, and Topper equivalent strain equation [57] is probably the most common method used to convert the strain amplitude for a given load cycle to the equivalent fully reversed strain amplitude. The equation may be expressed in the following form:

$$\left[\frac{\Delta \epsilon}{2} \right]_{eq} = \sqrt{\left(\frac{S_{max}}{E} \right) \left(\frac{\Delta \epsilon}{2} \right)}$$

Where, S is the applied stress, ϵ is the applied strain, and E is Young's Modulus for the material

3.7.1.3 Fatigue Notch Factor

For a given notched specimen geometry, the effect of the notch on the fatigue life is not simply a matter of determining the local stress from the stress concentration factor (K_t) and applying the strain-life data. There is an effect of the notch for the given material and notch radius. This effect is commonly known as the fatigue notch sensitivity (q).

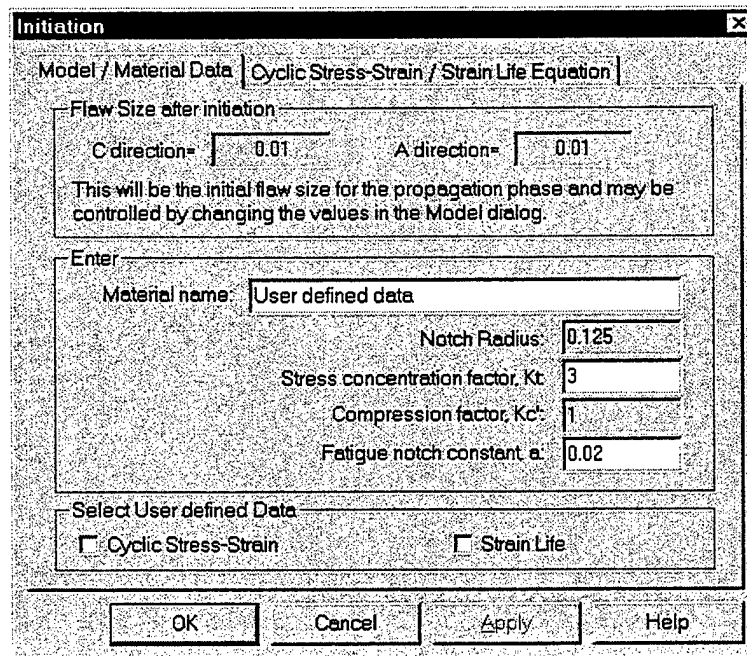
The Fatigue Notch Factor, (K_f), is essentially the K_t value corrected to account for the notch sensitivity for the given material [58]. It is determined as follows:

$$K_f = 1.0 + \frac{K_t - 1.0}{1.0 + \left(\frac{a}{r}\right)}$$

Where, a is an empirically determined material constant¹², and r is the notch root radius

3.7.2 Initiation Parameters

When the initiation parameters menu item is selected, the dialog shown in Figure 114 appears.



The dialog box is titled "Initiation" and has a close button (X) in the top right corner. It contains two tabs: "Model / Material Data" (selected) and "Cyclic Stress-Strain / Strain Life Equation".

Under the "Model / Material Data" tab, there is a section "Flaw Size after initiation" with two input fields: "C direction=" (value: 0.01) and "A direction=" (value: 0.01). Below these fields is a note: "This will be the initial flaw size for the propagation phase and may be controlled by changing the values in the Model dialog."

Below the "Flaw Size" section is a section "Enter" with a "Material name:" label and a text box containing "User defined data". To the right of this are four input fields: "Notch Radius:" (value: 0.125), "Stress concentration factor, K_t :" (value: 3), "Compression factor, K_c :" (value: 1), and "Fatigue notch constant, a :" (value: 0.02).

Below the "Enter" section is a section "Select User defined Data" with two checkboxes: "☐ Cyclic Stress-Strain" and "☐ Strain Life".

At the bottom of the dialog are four buttons: "OK", "Cancel", "Apply", and "Help".

Figure 114: Initiation Parameters Dialog

¹² Values of $[a]$ for some common materials may be found in sources like "Stress Concentration Factors," by R.E. Peterson

The parameter dialog is divided into two categories:

- Model/Material Data
- Cyclic Stress-Strain / Strain-Life Equation

AFGROW also includes an option to enter tabular stress-strain or strain-life data. These data are described in more detail in the following sections.

3.7.2.1 Model/Material Data

The model/material data dialog is shown in Figure 114.

Notch Radius (r): Physical radius of local notch (or hole) which is causing a local stress concentration.

Stress Concentration Factor (Kt): Stress concentration factor $\sigma_{\text{local}}/\sigma_{\text{ref}}$.

Compression Factor (Kc): Determines the amount of the applied compressive stress (fraction of applied tension) to be used in the initiation analysis - not currently active.

Fatigue Notch Constant (a): Material constant used to determine the Fatigue Notch Factor, K_f .

3.7.2.2 Cyclic Stress-Strain / Strain-Life Equation

The screenshot shows a software dialog box titled "Initiation" with a close button (X) in the top right corner. It has two tabs: "Model / Material Data" and "Cyclic Stress-Strain / Strain Life Equation", with the latter being the active tab. Inside the dialog, there is a section labeled "Enter" containing two equations:

- Cyclic Stress-Strain Equation: $\frac{\Delta \epsilon}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma}{2K} \right)^{\frac{1}{n}}$
- Strain Life Equation: $\frac{\Delta \epsilon}{2} = \left(\frac{\text{SIGF}}{E} \right) (2N_i)^b + \text{EPSF} (2N_i)^c$

Below the equations is a table of input fields for material coefficients:

Cyclic strength coefficient K:	74
Cyclic strain hardening exponent n:	0.032
Fatigue strength coefficient SIGF:	116
Fatigue strength exponent b:	-0.098
Fatigue ductility coefficient EPSF:	0.26
Fatigue ductility exponent c:	-0.73

At the bottom of the dialog are four buttons: "OK", "Cancel", "Apply", and "Help".

Figure 115: Cyclic Stress-Strain / Strain-Life Equation Dialog

Engineers have used the stress-strain and strain-life equations shown in Figure 115 for decades to estimate the fatigue initiation lives. The equations are curve fits to actual fatigue test data. The parameters for various materials are available in the open literature from several sources such as the ASM Handbook® [59]. The parameters are defined below:

Cyclic Strength Coefficient (K'): Stress Value at $\Delta\epsilon_p/2 = 1$ on a log plot of $\Delta\sigma/2$ vs. $\Delta\epsilon_p/2$

Cyclic Strain Hardening Exponent (n'): Slope of the log ($\Delta\sigma/2$) vs. log ($\Delta\epsilon_p/2$)

Fatigue Strength Coefficient (SIGF'): Stress Value at $2N_f = 1$ on a log plot of $\Delta\sigma/2$ vs. $2N_f$

Fatigue Strength Exponent (b): Slope of log ($\Delta\epsilon_e/2$) vs. log ($2N_f$)

Fatigue Ductility Coefficient (EPSF'): Plastic Strain Value at $2N_f = 1$ on a log plot of $\Delta\epsilon_p/2$ vs. $2N_f$

Fatigue Ductility Exponent (c): Slope of log ($\Delta\epsilon_p/2$) vs. log ($2N_f$)

Note: The subscripts e and p denote elastic and plastic values, respectively. The value $2N_f$ refers to cyclic reversals to failure (1 cycle = 2 reversals).

AFGROW includes a limited amount of strain-life data for a few common materials. These data are available by clicking on the “home” button on the initiation dialog as indicated in Figure 116.

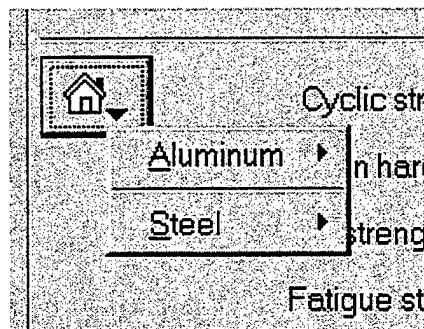


Figure 116: Using Default Initiation Parameters for Common Materials

These data are provided for users who may not have access to their own initiation data and want to use some generic aluminum or steel data.

3.7.3 User-Defined Cyclic Stress-Strain / Strain-Life Data

A user may choose to enter the Cyclic Stress-Strain data and/or the Strain-Life data in tabular form. The choice is controlled by the following check box controls in the initiation parameter dialog shown in Figure 117.

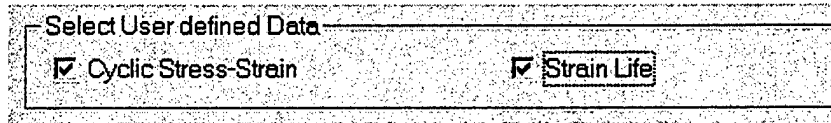


Figure 117: Options for User Defined Initiation Data

A new tab will appear for each box that is selected as shown in Figure 118.



Figure 118: Options for Stress-Strain and Strain-Life Input Data

The data must be entered in tabular format by selecting the appropriate tab. These data may be pasted from Excel or entered in the grid control by hand.

3.7.3.1 Cyclic Stress-Strain Data

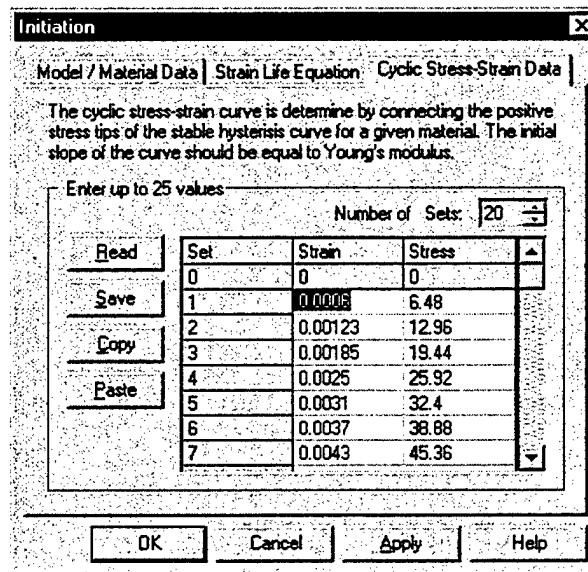


Figure 119: User-Defined Cyclic Stress-Strain Data

Cyclic stress-strain data are obtained from fully reversed cyclic load tests. These tests are conducted at several load levels where stress vs. strain data are obtained and monitored until the hysteresis curve (map of stress vs. strain for each cycle) becomes stabilized. The cyclic stress-strain curve is the locus of the tips of the stable hysteresis curves in the positive stress and strain quadrant of the plot (see Figure 120).

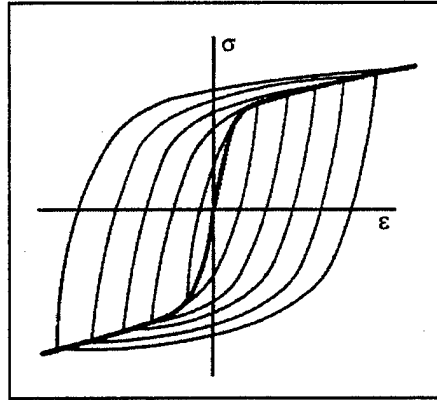


Figure 120: Stable Hysteresis Curves

The first point is defined at zero stress and zero strain. There is a linear range of stress vs. strain whose slope is equal to the Young's modulus of the material (by definition). AFGROW uses linear interpolation and extrapolation to determine the values between input points and beyond the last input point. This is the reason for requesting data for the linear range in addition to data that describes the non-linear behavior. It is a good idea to look at a plot of the initiation data in the main frame view (see Figure 15 in section 2.1.5). This option will permit the input data, the current Young's modulus, and any desired test data to be overlaid on the same plot. As may be imagined, the resulting crack initiation life is sensitive to the degree to which the input data match the actual test data.

3.7.3.2 Strain-Life Data

Initiation

Model / Material Data | Cyclic Stress-Strain Data | Strain Life Data

The Strain-Life data is for fully reversed ($R=-1$) loading. The life is given in reversals (cycles^2). It is important for the user to understand the definition of life (in terms of crack size) for which these data are valid.

Enter up to 25 values

Number of Sets: 18

Read	Set	Strain	Life
Save	1	0.23	1
Copy	2	0.14	2.51
Paste	3	0.086	6.3
	4	0.0539	15.84
	5	0.0346	39.8
	6	0.0231	100
	7	0.0161	251
	8	0.0117	630

OK Cancel Apply Help

Figure 121: User-Defined Strain-Life Data

The strain-life data are in terms of reversals instead of cycles. A reversal refers to a change in the loading direction during cyclic loading. A complete cycle consists of two load reversals. The first input point must be the strain to initiation (or perhaps failure) for

one reversal (monotonic loading). AFGROW uses logarithmic interpolation and extrapolation to determine the values between input points and beyond the last input point. The reason for this is to avoid any case where a negative strain value could result from an interpolation or extrapolation. It was also determined that logarithmic interpolation results in most accurate results. The resulting crack initiation life tends to be VERY sensitive to the degree in which the input data matches the actual test data. It is a good idea to look at a plot of the initiation data in the main frame view (see Figure 15 in section 2.1.5). This option will overlay the input data and any desired test data. As noted in the dialog, **IT IS VERY IMPORTANT** for the user to know the definition of life¹³ for the input data. This definition should be used in the initial crack length, which is input by the user for subsequent crack growth analysis. AFGROW will determine an initiation life from the input data and proceed with a crack growth analysis from the initial crack length(s) entered for the given problem.

3.7.4 Initiation/No Initiation

This option simply activates/deactivates the initiation analysis so a user may perform a life analysis for the same case with or without including the initiation life. If the initiation option is active, this menu item is shown as “No Initiation” and will deactivate the initiation analysis if selected. If the initiation option is not active, this menu item is shown as “Initiation” and will activate the initiation analysis. This may be useful when comparing results with and without including the time to crack initiation.

3.8 Window Menu

The three frames, discussed in detail in sections 2.1, 2.2, and 2.3, make up the views for the life prediction analysis. To allow the largest view of the spectrum when the view, spectrum plot option is selected (see Figure 90, section 3.3.9), the entire AFGROW window is used to display the spectrum. The window menu is used to control the display of the spectrum and the three AFGROW frames.

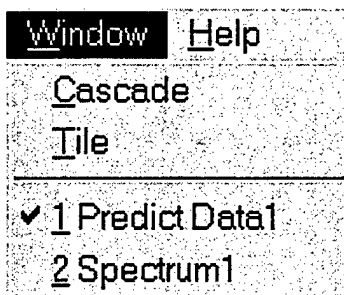


Figure 122: Window Menu

¹³ Crack length assumed as the definition of crack initiation

3.8.1 Window Cascade

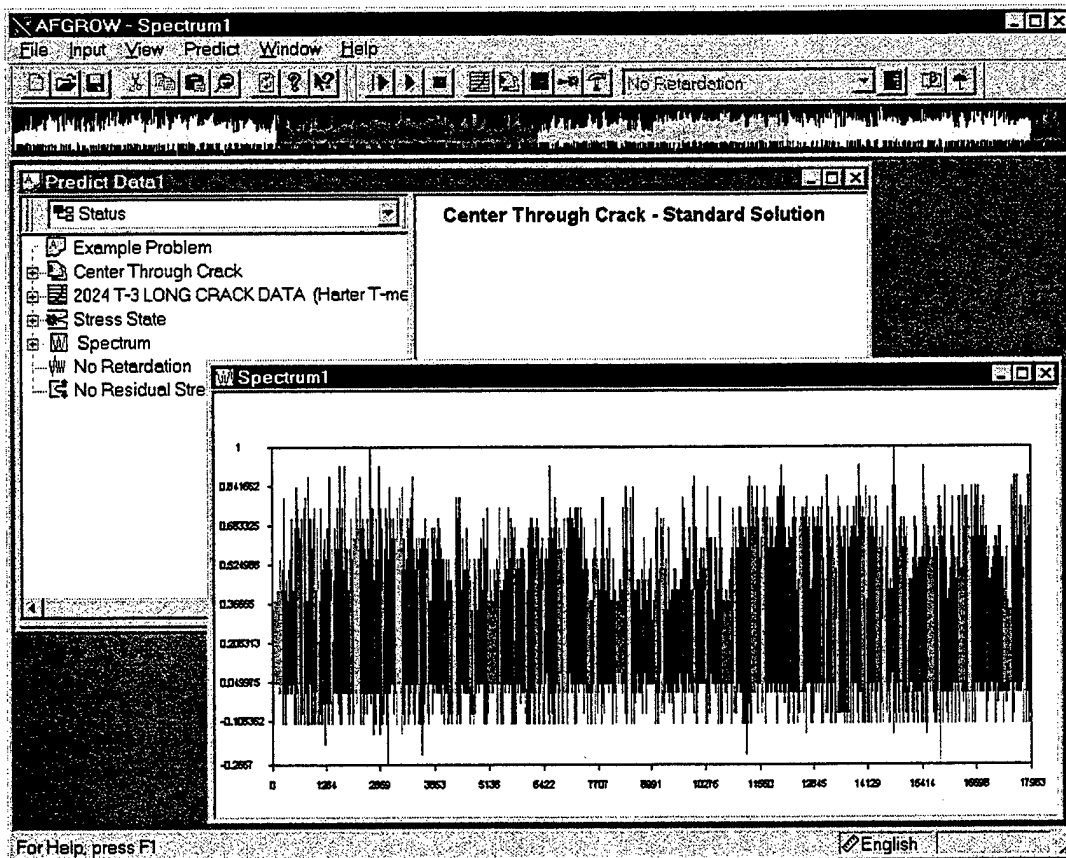


Figure 123: Cascade Window View

The cascade option shows both views overlapping each other. When the spectrum view is active (blue title bar), the menu options related to the prediction data are either grayed out or removed. Activating the prediction view returns the menu to normal. Users can switch between prediction data and spectrum views by clicking on the appropriate title bar or selecting the desired view in the Window menu (Figure 122).

Both views will be reduced in size to fit within the AFGROW window. The three frames of the prediction view will be automatically reduced in size. The output frame may not be visible. The frames can be resized by dragging the frame boundaries with the mouse as desired. The views can also be minimized, restored, or maximized using the standard Windows tools in the upper right hand corner of either view.

3.8.2 Window Tile

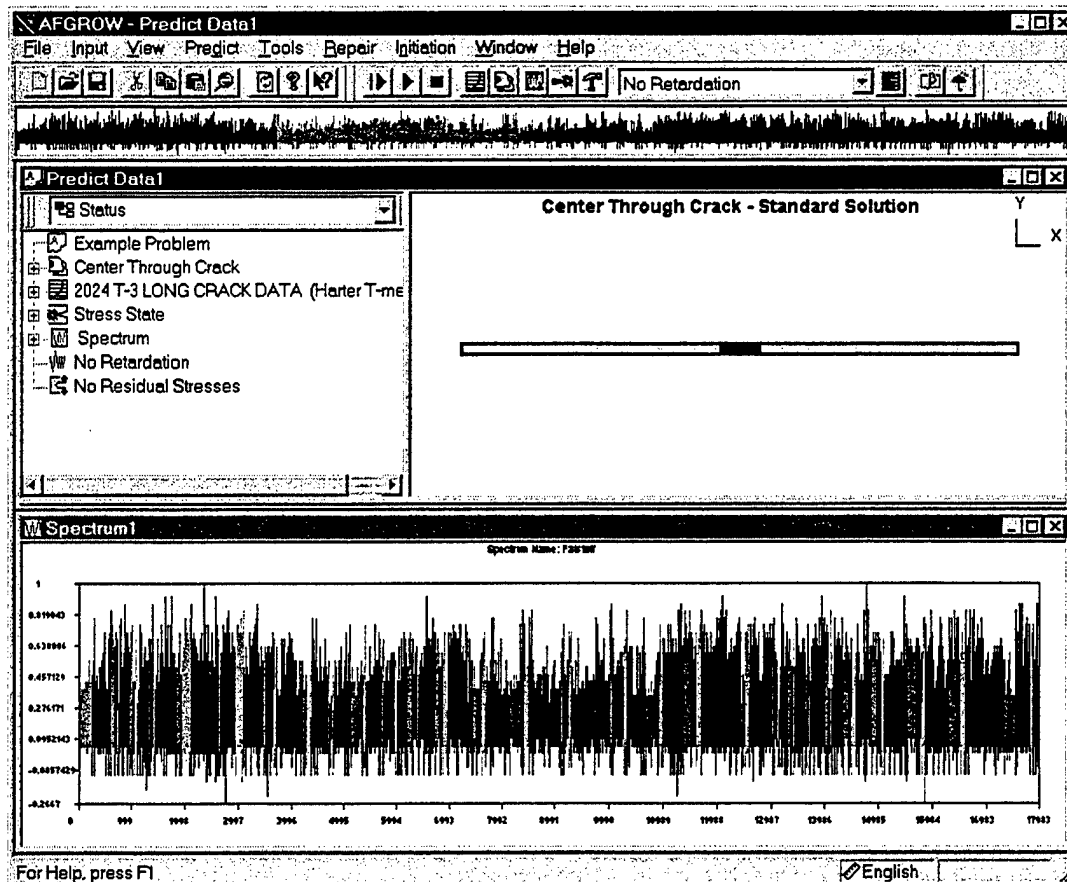


Figure 124: Tile Window View

The tile option shows both views above and below each other. When the spectrum view is active (blue title bar), the menu options related to the prediction data are either grayed out or removed. Activating the prediction view returns the menu to normal. Users can switch between prediction data and spectrum views by clicking on the appropriate title bar or selecting the desired view in the Window menu (Figure 122).

Both views will be reduced in size to fit within the AFGROW window. The three frames of the prediction view will be automatically reduced in size. The output frame may not be visible. The frames can be resized by dragging the frame boundaries with the mouse as desired. The views can also be minimized, restored, or maximized using the standard Windows tools in the upper right hand corner of either view.

3.9 Help Menu

As with most windows programs, AFGROW includes a help menu, which includes extensive on-line help (Help Topics) and version information (About AFGROW).

3.9.1 Help Topics

This action allows you to access the on-line help that is available for the Win95/98/NT4 version of AFGROW. The Help Topics dialog is shown in Figure 112.

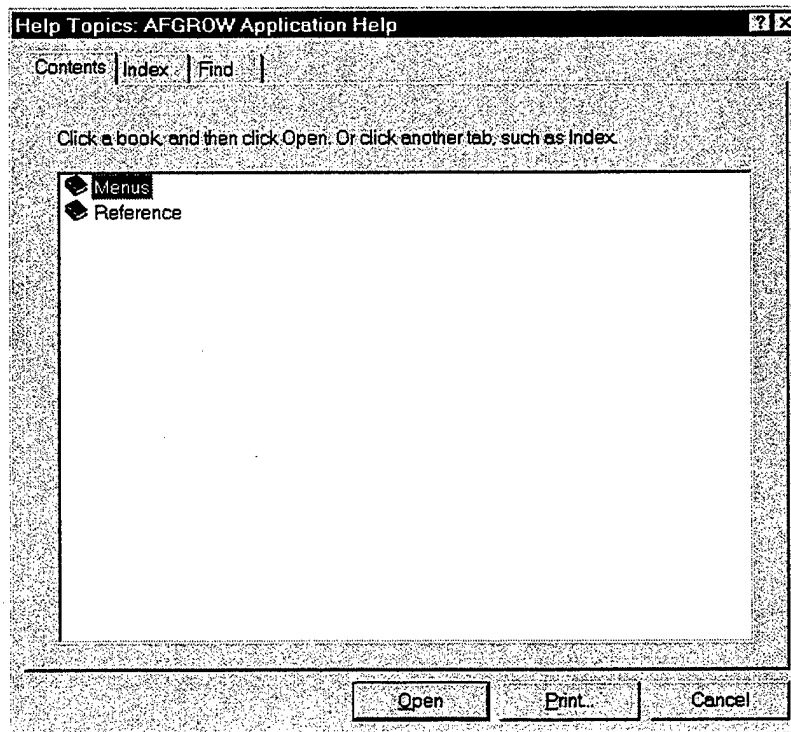


Figure 125: AFGROW Help Topics

This help is the standard Windows help where users can select a topic, view the index, or search for a keyword. Help is available directly from the keyboard for any open dialog by using the F1 function key. There is also a black question mark tool in the AFGROW standard toolbar (see Figure 88, section 3.3.1) that may be used to select help for any item in the menus or any other toolbar shortcut. You just click on the question mark (the cursor becomes a question mark) and click again on the item of interest in the AFGROW main window.

3.9.2 About AFGROW

This action allows users to view information about the version of AFGROW being used. The About AFGROW dialog is shown in Figure 126.

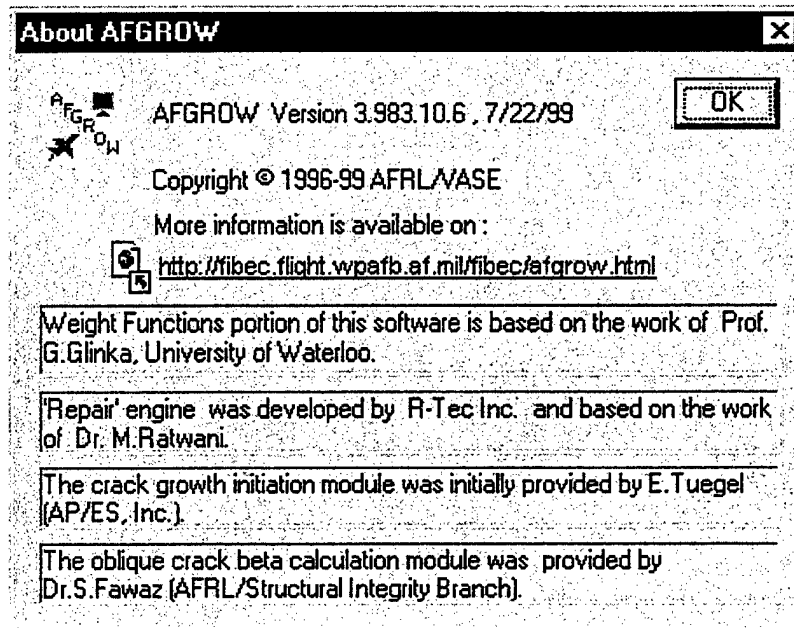


Figure 126: Help About AFGROW

4.0 ENGLISH AND METRIC UNITS

AFGROW uses either English¹⁴ or Metric¹⁵ units of measurement.

The units used in AFGROW are controlled by the choice of the units displayed on the status bar (see Figure 20, section 2.6). Users may switch between English and Metric units by clicking on the small ruler on the status bar and selecting the units of choice as shown in Figure 127.

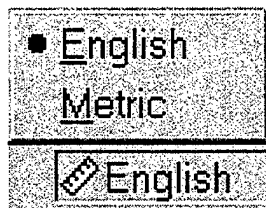


Figure 127: Switching Between English and Metric Units

The current system of units may be changed by clicking (right or left) on the units icon on the status bar and selecting the units of choice. The units may be changed at any time and all input parameters will be converted accordingly. AFGROW uses ASTM Standard Metric Practices [60] for all internal conversions. Care has been taken to prevent loss of data precision after multiple conversions. However, some rounding may be experienced for some small numbers relative to standard values. However, Values that are known to be small (i.e., Paris C, Coefficient of Thermal Expansion, etc.) are handled correctly internally.

For example:

If users prefer to work in Metric units and certain data are available in English units, users can switch to English units, enter these data, and switch back to Metric units (or vice versa).

AFGROW users **MUST** remember to be consistent in the use of units within the English or Metric Systems. The AFGROW output data will be consistent with the units selected by the user.

Some users may ask why the metric units of length are meters. The reason is consistency. It was felt that since the standard metric units for stress intensity is $MPa\sqrt{meter}$, the length units should be in meters. This consistency is important in AFGROW for internal calculations.

¹⁴ Length – inches, Force – Kpounds, Stress – Ksi, Temperature – Degrees Fahrenheit

¹⁵ Length – meters, Force – MNewtons, Stress- MPa, Temperature – Degrees Centigrade

5.0 COMPONENT OBJECT MODEL SERVER

AFGROW for Windows95/98/NT4® operates in two different modes; first, as a normal interactive Windows program, and second, as a Component Object Model (COM) Server [9]. The COM server technology is an outgrowth of the Object Linking and Embedding technology used by Microsoft for many years. A COM Server may be called from other Windows software and the results from the server can be sent back to the calling program. In the case of AFGROW, users can write Windows programs or macros to generate input data, and call AFGROW to perform structural life analyses. AFGROW can perform the life analyses and return the results directly to the calling software. The most commonly used application of this capability is seen in the following example, Figure 128, using Microsoft Excel®.

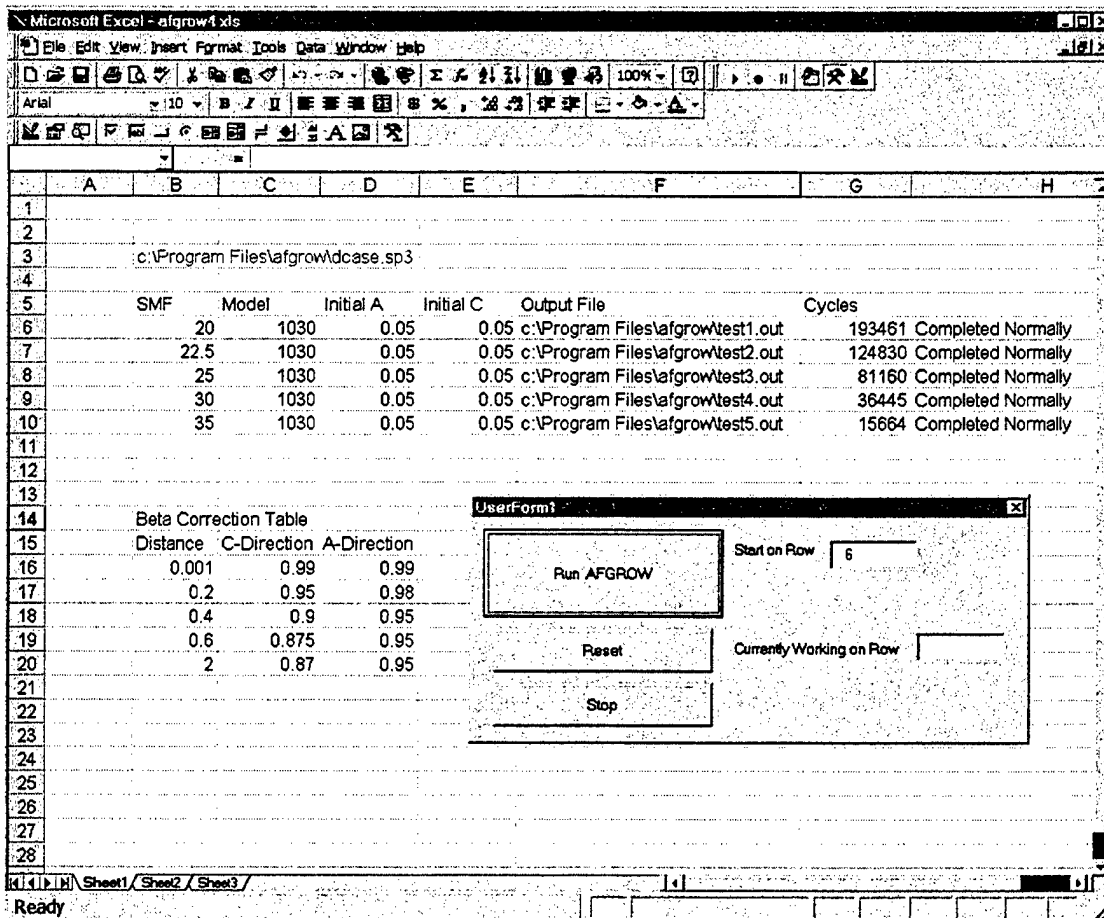


Figure 128: Microsoft Excel Macro Using AFGROW

The above example is a fairly simple application of the COM capabilities in AFGROW, but is intended to show how the technology may be used to perform multiple life analyses. Other uses of this capability can extend as far as a user's imagination can carry it in terms of application to structural life prediction. This capability has already been

used to estimate the crack growth life of specimens subjected to a corrosive environment [61].

An extensive manual on the use of AFGROW as a COM server has been released on the AFGROW Web Site [62] and will soon be available in print [63]. An excerpt from the manual is given below:

General Instructions

Before using the server version from another windows program, AFGROW MUST run at least once as a stand-alone program. When the server version is executed for the first time, Windows will recognize that it is a COM server and will look for a Type Library Binary (TLB) file (*afgrow.tlb*) and register AFGROW as a COM object on the local machine. Once this is complete, the AFGROW server will be available for use by other COM compatible software.

The TLB file contains detailed information that other programs use to determine which variables and sub-routines are available in AFGROW. Whenever the AFGROW server is updated and a new version is downloaded, all references to the previous server version MUST be updated.

Again, remember that the new server version will still function as the stand-alone interactive code as it has in the past. The new capability is merely an addition to AFGROW, which we hope users will find useful.

6.0 TUTORIAL

This section will take users through a sample problem to show how to use many of the features described in previous sections of this manual.

6.1 Problem Definition

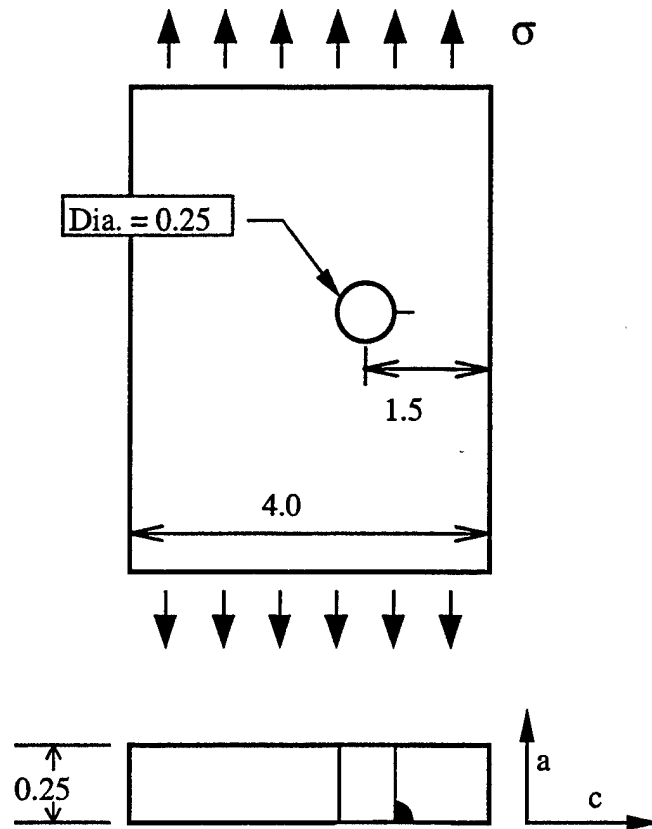


Figure 129: Sample Problem Geometry

Specimen Geometry:	Corner Crack at an Offset Hole in a Plate
Dimensions:	$W = 4.0$ in., $T = 0.25$ in., Dia. = 0.25 in.
Hole Offset:	$B = 1.5$ in.
Initial Crack Size:	$c = 0.05$ in., $a = 0.05$ in.
Material:	7050-T74 Plate (from matfile.da3)
Stress Spectrum:	16 Ksi to 0 Ksi 1 Cycle 12 Ksi to 8 Ksi 1000 Cycles
Retardation Model:	Generalized Willenborg Model, SOR = 2.8
Stress State:	Automatic
Beta Correction:	None
Environment:	N/A

Residual Stresses:

r	Residual Stress (r,0)	Residual Stress (0,r)
0.000	-2.40	-2.40
0.002	-1.20	-2.40
0.004	0.00	-2.40
0.100	0.40	-2.40
0.250	0.35	-2.40
0.500	0.30	0.00
1.000	0.28	0.00

Predict Preferences:

Use Defaults except set the growth increment to cycle by cycle beta and spectrum calculations, and the print interval to 0.05 inches.

6.2 Entering Data in AFGROW

AFGROW is written such that the user may enter data in any order. The philosophy is that the user should control the software; the software shouldn't control the user. The only exception to this general philosophy occurs in the case of the bonded repair analysis option. In the bonded repair case, the effect of the repair is dependent on the applied stress level, specimen dimensions, and material properties. The order in which the data are entered in the following section is simply the preference of the author.

6.2.1 Input Title

Title [X]

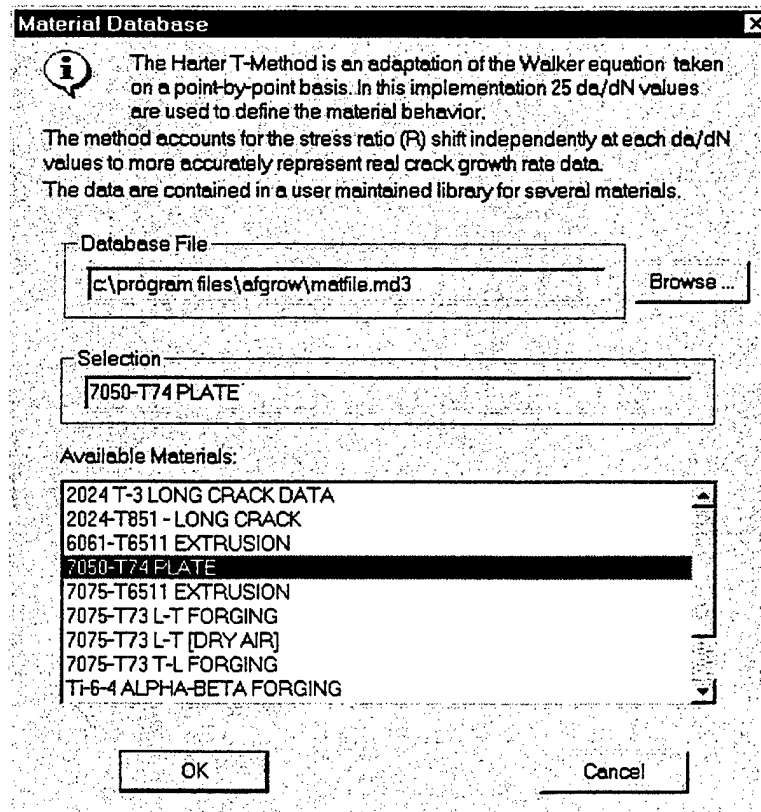
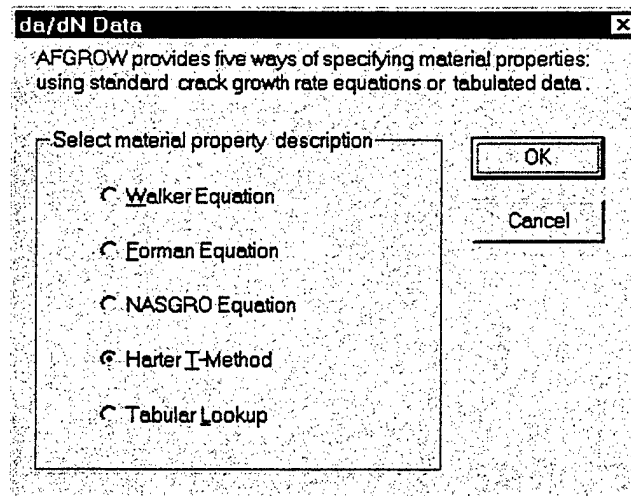
Provide identifying information associated with an input file or problem definition.

Enter

Title:

Comments:

6.2.2 Input Material



6.2.3 Input Model

Model Geometry and Dimensions

Geometry | Dimension | Load

Standard Solutions | Weight Function Solutions

Select crack geometry by clicking on corresponding icon

Model	Description of the Configurations	Base Solution
<input type="checkbox"/>	Center Semi-elliptic Surface Flaw	Application Defined
<input type="checkbox"/>	Center Semi-elliptic Edge Surface ...	Application Defined
<input type="checkbox"/>	Center Full-elliptic Embedded Flaw	Application Defined
<input checked="" type="checkbox"/>	Single Corner Crack at Hole	Application Defined
<input type="checkbox"/>	Single Surface Crack at Hole	Application Defined
<input type="checkbox"/>	Double Corner Crack at Hole	Application Defined
<input type="checkbox"/>	Double Surface Crack at Hole	Application Defined
<input type="checkbox"/>	Single Edge Corner Crack	Application Defined

OK Cancel Apply Help

Preview

Model Geometry and Dimensions

Geometry | Dimension | Load

Model dimensions are initialized to default values at start-up or when a new model configuration is selected.

Enter specimen dimensions

Width (W): 4

Thickness (T): 0.25

Hole Diameter (D): 0.25

Offset Hole

Hole Offset (B): 1.5

Enter crack dimensions

Crack Length - 'C' Direction: 0.05

Crack Length - 'A' Direction: 0.05

☐ Keep 'A/C' constant ☐ Oblique through crack

OK Cancel Apply Help

Preview

Model Geometry and Dimensions

Geometry | Dimension | Load

For some models AFGROW allows to combine multiple load case solutions. The ratio of the tension, bending or bearing stress to the reference stress must be input for each load case.

Tension

Crack plane

Filled Unloaded Hole

Stress Ratio: 1

Bending

Crack plane

Stress Ratio: 0

Bearing

Crack plane

Stress Ratio: 0


Calculator Calculate Bearing Stress Ratio

OK Cancel Apply Help

Preview

6.2.4 Input Spectrum

Spectrum

 **Stress Multiplication Factor (SMF):** multiplies the stress or load levels found in spectrum files. This allows normalized spectra to be used. If actual stress levels are presented in spectrum files, SMF must be set to 1.

Residual Stress Strength Requirement (SPCMX): is used for critical crack size determination, if a value other than zero is entered.

SPCMX: value of stress (or load for models using load instead of stress input) which the structure MUST be able to carry at all crack sizes.

Enter

Stress Multiplication Factor (SMF):

Residual Stress Strength Requirement (SPCMX):

Select

☒ Create new spectrum file

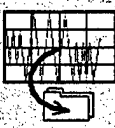
☐ Open spectrum file

☐ Constant amplitude loading

OK

Cancel

Dialog

 The Spectrum Wizard creates SPECTRUM INFORMATION FILE which is required to define the load/stress history for a given crack growth analysis.

Spectra may be broken into several sub-spectra and sub-spectra may be grouped and divided among a number of sub-spectrum files.

Enter

Base Filename (no extension):


Spectrum Title:

Label for Sub-spectrum:

Number of files:

< Back Next > Cancel Help

Type of spectrum

 A cycle by cycle spectrum is one in which each max-min load/stress is applied for one (1) cycle. This may be thought of as a real time spectrum. The blocked spectrum is one where each max-min pair is applied for some finite number of cycles.

Many times, spectra are presented in this format to save computer time and space.

In many cases, the use of the blocked format produces very little difference in terms of the analysis. In general, the more times a spectrum is repeated, the less the difference in using blocked or cycle-by-cycle spectra.

Select Type of Spectrum


☒ Blocked Cycles

☐ Cycle by Cycle

< Back Next > Cancel Help



Number of Sub-spectra


 There are limits, in manual mode, placed on the number of sub-spectra that can make up a spectrum. The limits are 10 sub-spectra per file.

Enter Number of Sub-spectra in file #1

Number of Sub-spectra:

☐ Import from file

Number of Stress levels

 There are limits, in manual mode, placed on the number of stress levels that can make up a spectrum. The limits are 25 levels per spectrum.


File #1 Sub-spectrum #1

Enter Number of stress levels

Number of Stress levels:

☐ Import single subspectrum from file

Stress levels

 File #1 Sub-spectrum #1

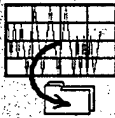
Input Spectrum Stress /Load Levels information in the following format.

Enter Stress Levels

Set	Max.	Min.	Cycles
1	16.000000	0.000000	1
2	12.000000	8.000000	1000



The Last One



The Spectrum Wizard finished creation of the Spectrum. The Spectrum referred from here is the ENTIRE Spectrum including all of the spectrum files.

Spectrum CREATED but NOT OPENED ... press OPEN to open Spectrum and leave or FINISH to leave without opening Spectrum.

Spectrum Parameters

Base File:	AFGROW Tutorial Sample Spectrum
Spectrum Title:	C:\Program Files\AFGROW\sample.sp3
Label to sub-spectrum:	Block
Number of files:	1
Type of Spectrum:	Blocked

6.2.5 Input Retardation

Retardation

Retardation models used to account for the effect of load sequence of crack growth rate.

Select


☐ No Retardation

☒ Willenborg Model...

☐ Closure Model...

☐ Wheeler Model...

Willenborg Retardation Parameters

 The Willenborg model uses an 'effective' stress intensity factor based on the size of yield zone in front of the crack tip to account for the effect of load sequence on crack growth rate.

Enter

Shutoff Overload Ratio (SOLR):

6.2.6 Stress State

Stress State

i The Stress State Data provide a means of approximating the actual value of yield zone size and fracture toughness in each crack growth direction.

Select:

☒ Determine Stress State automatically

☐ Enter Stress State manually

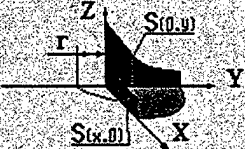
OK

Cancel

6.2.7 Residual Stresses

Residual Stresses

i AFGROW offers the option to model the effect of residual stresses on crack growth by reading in a table of residual stresses as a function of crack length, then AFGROW uses these values to generate a table of 'Residual Stress Intensity Factors' (SIF).



$S(x,y)$ - value of a stress in Z axis direction.
 r - distance from the center point of the crack along X or Y axis.

Select type of Data:

☒ Stress ☐ Residual K

Enter stress and 'r'. Use up to 25 sets

Number of Sets:

Set	r	$S(r,0)$	$S(0,r)$
1	0	-2.4	-2.4
2	0.02	-1.2	-2.4
3	0.04	0	-2.4
4	0.1	0.4	-2.4
5	0.25	0.35	-2.4
6	0.5	0.3	0

Generate SIF table using:

☒ Gauss Integration ☐ Weight Function

File:

Open


Save


OK Cancel No Stresses

6.2.8 Predict Preferences

Predict Function Preferences [X]

Growth Increment | Output Intervals | Output Options | Pro [Left Arrow] [Right Arrow]

 AFGROW uses the Vroman integration technique when a blocked spectrum is input. To minimize an error in predicted crack propagation times it is not recommended for Max Growth Increment value to exceed 10%.

 Cycle by cycle calculation can significantly increase a calculation time.

Select

☒ Cycle by Cycle Spectrum calculation

☒ Cycle by Cycle Beta and Spectrum calculation

OK Cancel Save Default

Predict Function Preferences [X]

Growth Increment | Output Intervals | Output Options | Pro [Left Arrow] [Right Arrow]

Print Output Data at

☒ Specified Crack Growth Increment

☐ Specified Spectrum Cyclic Increment

☐ After each Spectrum Stress Level

Crack Growth

☐ Display Lifetime in Hours

OK Cancel Save Default

6.3 AFGROW Output

The results of the AFGROW analysis are given below.

Single Corner Crack at an Offset Hole

Includes Residual Stress

J. Harter 23 Jul 99

AFGROW v3.983.10.6: 7/23/1999 15:44

**English Units [Length(in), Stress(Ksi), Temperature(F)]

Crack Growth Model and Spectrum Information

Title: Sample Tutorial Problem

Crack Model: 1030 - Single Corner Crack at Hole

Load: Tension Stress Ratio: 1, Bending Stress Ratio: 0, Bearing Stress Ratio: 0

Initial crack depth (a) : 0.0500
Initial surface crack length (c): 0.0500

Thickness : 0.250
Width : 4.000
Hole Diameter: 0.250
Hole Offset: 1.500

Young's Modulus =10400
Poisson's Ratio =0.33
Coeff. of Thermal Expan. =1.34e-005

WILLENBORG shut-off ratio : 2.800
Determine Stress State automatically (2 = Plane stress, 6 = Plane strain)

The stress intensity factors are being adjusted for a
residual stress field as follows:

A	Stress	Residual K	C	Stress	Residual K
0.0000	-2.4000	-0.076139	0.0000	-2.4000	-0.076169
0.0200	-2.4000	-0.732505	0.0200	-1.2000	-0.517797
0.0400	-2.4000	-0.939953	0.0400	0.0000	-0.254020
0.1000	-2.4000	-1.364590	0.1000	0.4000	-0.059487
0.2500	-2.4000	-2.482494	0.2500	0.3500	-0.226042
0.5000	0.0000	-0.264293	0.5000	0.3000	0.132328
1.0000	0.0000	0.002428	1.0000	0.2800	0.428985

Tabular crack growth rate data are being used

For $R_{eff} < 0.0$, K_{max} is used in place of ΔK

Material: 7050-T74 PLATE

Rate	Delta k	M
1.000e-009	2.000	0.670
4.000e-009	2.020	0.670
1.000e-008	2.040	0.680
2.000e-008	2.060	0.700
4.000e-008	2.150	0.740
7.000e-008	2.400	0.740
1.000e-007	2.800	0.680
2.000e-007	3.850	0.550
4.000e-007	5.300	0.380
7.000e-007	6.350	0.290
1.000e-006	7.000	0.270
2.000e-006	8.350	0.300
4.000e-006	9.800	0.350
7.000e-006	11.000	0.400
1.000e-005	12.100	0.450
2.000e-005	15.500	0.500
4.000e-005	19.300	0.570
7.000e-005	23.000	0.620
1.000e-004	26.000	0.630
2.000e-004	31.915	0.560
4.000e-004	39.537	0.470
7.000e-004	47.206	0.390
1.000e-003	52.000	0.340
4.000e-003	65.000	0.240
1.000e-002	70.000	0.200

Lower 'R' value boundary: -0.33

Upper 'R' value boundary: 0.8

Plane strain fracture toughness: 33

Yield stress: 65

Failure is based on the current load in the applied spectrum

Cycle by cycle beta and spectrum calculation

****Spectrum Information**

AFGROW Tutorial Sample Spectrum

Spectrum multiplication factor: 1

The spectrum will be repeated up to 999999 times

Critical Crack Length is Based on the Maximum Spectrum Stress

Critical crack size in 'C' direction=1.31674, Stress State=2 (Based on K_{max} criteria)

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.05 1.344 -0.027 -0.027 8.303e+000 2.113e-006
 A 0.05 1.643 -0.107 -0.107 9.408e+000 4.502e-006
 Residual K in A direction= -1.0107; Residual K in C direction= -0.2216
 A/t ratio = 0.2 A/C ratio = 1

Max stress = 16.000000 R = 0.00
 0 Cycles Block: 1 Pass: 1

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.085624 1.281 0.612 0.612 2.658e+000 2.543e-007
 A 0.1 1.351 0.539 0.539 3.029e+000 2.990e-007
 Residual K in A direction= -1.3646; Residual K in C direction= -0.1061
 A/t ratio = 0.4 A/C ratio = 1.1679

Max stress = 12.000000 R = 0.67
 196391 Cycles Block: 197 Pass: 197

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.1 1.239 0.622 0.622 2.777e+000 3.289e-007
 A 0.11622 1.297 0.546 0.546 3.134e+000 3.492e-007
 Residual K in A direction= -1.4855; Residual K in C direction= -0.0595
 A/t ratio = 0.4649 A/C ratio = 1.1622

Max stress = 12.000000 R = 0.67
 243722 Cycles Block: 244 Pass: 244

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.13551 1.159 0.638 0.638 3.024e+000 6.144e-007
 A 0.15 1.213 0.556 0.556 3.332e+000 4.915e-007
 Residual K in A direction= -1.7372; Residual K in C direction= -0.0989
 A/t ratio = 0.6 A/C ratio = 1.1069

Max stress = 12.000000 R = 0.67
 328185 Cycles Block: 328 Pass: 328

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.15 1.134 0.612 0.612 3.114e+000 5.520e-007
 A 0.16134 1.194 0.519 0.519 3.401e+000 4.216e-007
 Residual K in A direction= -1.8218; Residual K in C direction= -0.1150
 A/t ratio = 0.64537 A/C ratio = 1.0756

Max stress = 12.000000 R = 0.67
 352548 Cycles Block: 353 Pass: 353

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.2 1.085 0.628 0.628 3.440e+000 1.037e-006
 A 0.19465 1.162 0.530 0.530 3.636e+000 6.276e-007
 Residual K in A direction= -2.0700; Residual K in C direction= -0.1705
 A/t ratio = 0.77858 A/C ratio = 0.97322

Max stress = 12.000000 R = 0.67
 411889 Cycles Block: 412 Pass: 412

Crack size Beta R(k) R(eff) Delta-K D()/DN

C 0.2087 1.079 0.621 0.621 3.495e+000 1.045e-006
A 0.2 1.159 0.521 0.521 3.674e+000 6.214e-007
Residual K in A direction= -2.1099; Residual K in C direction= -0.1802
A/t ratio = 0.8 A/C ratio = 0.95834

Max stress = 12.000000 R = 0.67
419777 Cycles Block: 420 Pass: 420

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.25 1.062 0.613 0.613 3.765e+000 1.276e-006
A 0.22459 1.144 0.508 0.508 3.845e+000 7.064e-007
Residual K in A direction= -2.2931; Residual K in C direction= -0.2260
A/t ratio = 0.89837 A/C ratio = 0.89837

Max stress = 12.000000 R = 0.67
451684 Cycles Block: 452 Pass: 452

Transitioned to a thru-crack at 95% thickness penetration

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.27312 1.056 0.658 0.658 3.914e+000 1.955e-006
A 0.2375 1.137 0.553 0.553 3.930e+000 1.039e-006
Residual K in A direction= -2.3893; Residual K in C direction= -0.1929
A/t ratio = 0.95 A/C ratio = 0.86959

Max stress = 12.000000 R = 0.67
466237 Cycles Block: 466 Pass: 466

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.27312 1.078 0.661 0.661 3.994e+000 2.135e-006
Residual K in C direction= -0.1929

Max stress = 12.000000 R = 0.67
466237 Cycles Block: 466 Pass: 466

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.3 1.053 0.647 0.647 4.088e+000 2.095e-006
Residual K in C direction= -0.1544

Max stress = 12.000000 R = 0.67
480074 Cycles Block: 479 Pass: 479

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.35 1.016 0.645 0.645 4.262e+000 2.371e-006
Residual K in C direction= -0.0827

Max stress = 12.000000 R = 0.67
503018 Cycles Block: 502 Pass: 502

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.4 0.990 0.608 0.608 4.439e+000 2.170e-006
Residual K in C direction= -0.0110

Max stress = 12.000000 R = 0.67
522576 Cycles Block: 522 Pass: 522

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.45 0.971 0.668 0.668 4.619e+000 3.571e-006
Residual K in C direction= 0.0607

Max stress = 12.000000 R = 0.67
539449 Cycles Block: 538 Pass: 538

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.5 0.958 0.657 0.657 4.804e+000 3.788e-006
Residual K in C direction= 0.1323

Max stress = 12.000000 R = 0.67
554051 Cycles Block: 553 Pass: 553

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.55 0.950 0.617 0.617 4.996e+000 3.380e-006
Residual K in C direction= 0.1620

Max stress = 12.000000 R = 0.67
566657 Cycles Block: 566 Pass: 566

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.6 0.946 0.619 0.619 5.196e+000 3.902e-006
Residual K in C direction= 0.1917

Max stress = 12.000000 R = 0.67
577682 Cycles Block: 577 Pass: 577

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.65 0.946 0.671 0.671 5.407e+000 6.082e-006
Residual K in C direction= 0.2213

Max stress = 12.000000 R = 0.67
587291 Cycles Block: 586 Pass: 586

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.70001 0.949 0.608 0.608 5.631e+000 4.842e-006
Residual K in C direction= 0.2510

Max stress = 12.000000 R = 0.67
595595 Cycles Block: 595 Pass: 595

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.75 0.957 0.654 0.654 5.874e+000 7.150e-006
Residual K in C direction= 0.2807

Max stress = 12.000000 R = 0.67
602947 Cycles Block: 602 Pass: 602

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 0.80001 0.968 0.672 0.672 6.138e+000 8.572e-006
Residual K in C direction= 0.3103

Max stress = 12.000000 R = 0.67
609416 Cycles Block: 608 Pass: 608

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.85001 0.984 0.672 0.672 6.431e+000 9.579e-006
 Residual K in C direction= 0.3400

Max stress = 12.000000 R = 0.67
 615213 Cycles Block: 614 Pass: 614

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.90001 1.005 0.673 0.673 6.761e+000 1.076e-005
 Residual K in C direction= 0.3697

Max stress = 12.000000 R = 0.67
 620358 Cycles Block: 619 Pass: 619

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 0.95001 1.033 0.651 0.651 7.138e+000 1.124e-005
 Residual K in C direction= 0.3993

Max stress = 12.000000 R = 0.67
 624925 Cycles Block: 624 Pass: 624

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 1 1.069 0.648 0.648 7.579e+000 1.280e-005
 Residual K in C direction= 0.4290

Max stress = 12.000000 R = 0.67
 628913 Cycles Block: 628 Pass: 628

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 1.05 1.116 0.672 0.672 8.109e+000 1.629e-005
 Residual K in C direction= 0.4290

Max stress = 12.000000 R = 0.67
 632353 Cycles Block: 631 Pass: 631

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 1.1 1.178 0.672 0.672 8.763e+000 1.942e-005
 Residual K in C direction= 0.4290

Max stress = 12.000000 R = 0.67
 635282 Cycles Block: 634 Pass: 634

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 1.15 1.263 0.609 0.609 9.606e+000 1.960e-005
 Residual K in C direction= 0.4290

Max stress = 12.000000 R = 0.67
 637671 Cycles Block: 637 Pass: 637

Crack size Beta R(k) R(eff) Delta-K D()/DN
 C 1.2 1.385 0.671 0.671 1.076e+001 3.121e-005
 Residual K in C direction= 0.4290

Max stress = 12.000000 R = 0.67
 639587 Cycles Block: 638 Pass: 638

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 1.25 1.576 0.655 0.655 1.249e+001 4.231e-005
Residual K in C direction= 0.4290

Max stress = 12.000000 R = 0.67
641009 Cycles Block: 640 Pass: 640

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 1.3001 1.931 0.645 0.645 1.561e+001 7.107e-005
Residual K in C direction= 0.4290

Max stress = 12.000000 R = 0.67
641907 Cycles Block: 641 Pass: 641

*****Fracture based on 'Kmax' Criteria (current maximum stress)

Crack size Beta R(k) R(eff) Delta-K D()/DN
C 1.3456 2.830 0.669 0.669 2.327e+001 5.675e-004
Residual K in C direction= 0.4290

Max stress = 12.000000 R = 0.67
642253 Cycles Block: 641 Pass: 641

Stress State in 'C' direction (PSC): 2

Fracture has occurred - run time : 0 hour(s) 0 minute(s) 37 second(s)

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